IND Cubesat Communications Briefing

10 November 2015

Welcome and Introduction

Sami Asmar

Jet Propulsion Laboratory
California Institute of Technology

Briefing Agenda

- Introductions – Sami Asmar
- IND Communications Policy – Les Deutsch
- Strategy for Cubesats and the DSN – Doug Abraham
- DSN Approach and Anomaly Response – Jeff Berner
- Spectrum Management – Feiming Morgan
- Other Ground System and Navigation Services – Eleanor Basilio
- Iris Radio Overview – Courtney Duncan or Kris Angkasa
- Questions & Discussions

IND Cubesat Briefing/Technical Exchange
10 November 2015

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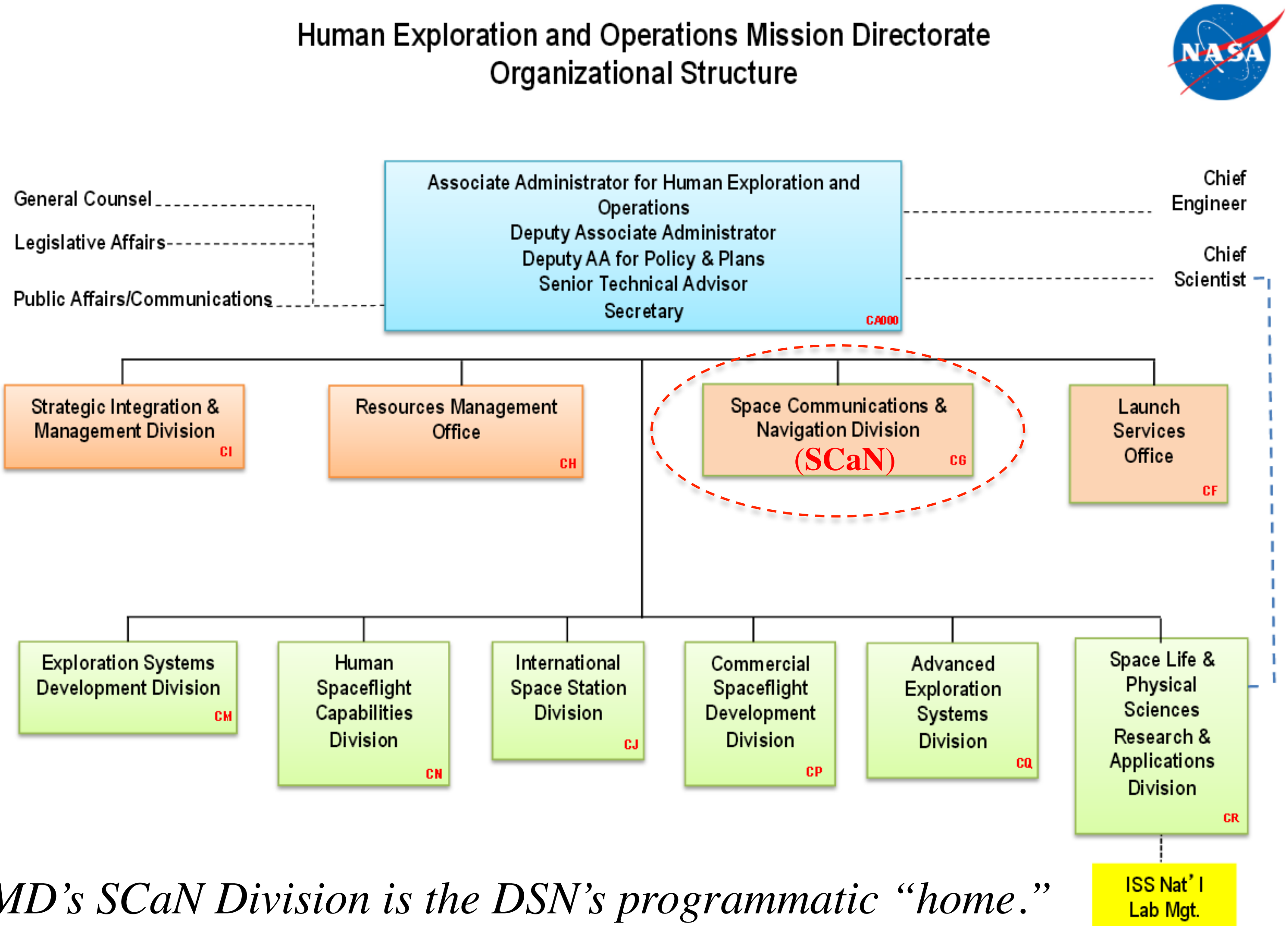
IND Communications Policy
Les Deutsch

Topics

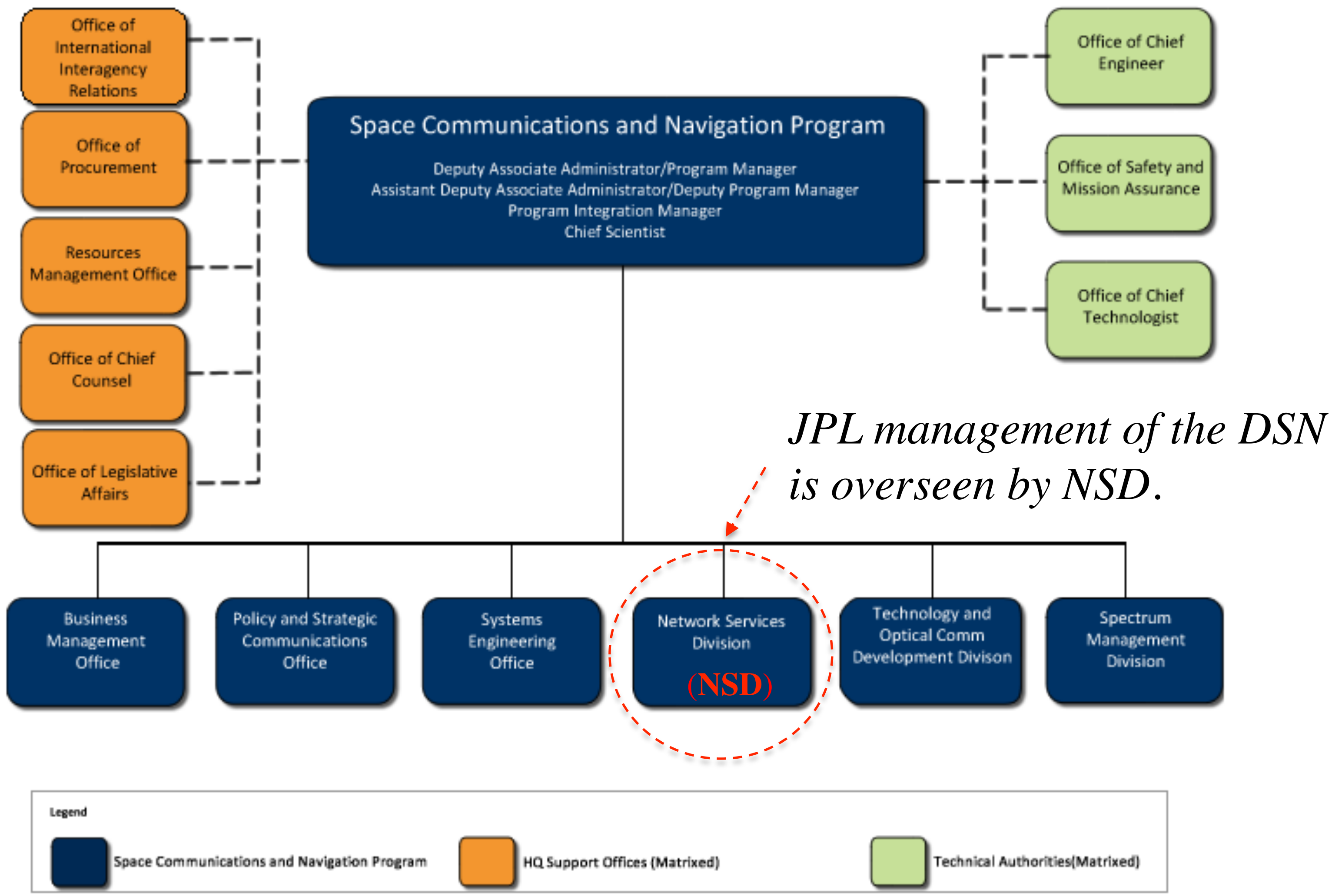
- **Organizations and Roles**
  - DSN Organizational Context & Roles
  - AMMOS Organizational Context & Roles
- **Deep Space Definition**
  - From an Operational Perspective
  - From a Spectrum Allocation Perspective
- **Key Personnel Roles and Policy Considerations**
  - Spectrum, DSN/AMMOS POC, Cross Support POC
- **Class D vs. Class A Service Expectation**
  - More in DSN Engineering Approach & Anomaly Response

DSN Organizational Context (1/3)



HEOMD's SCaN Division is the DSN's programmatic "home."

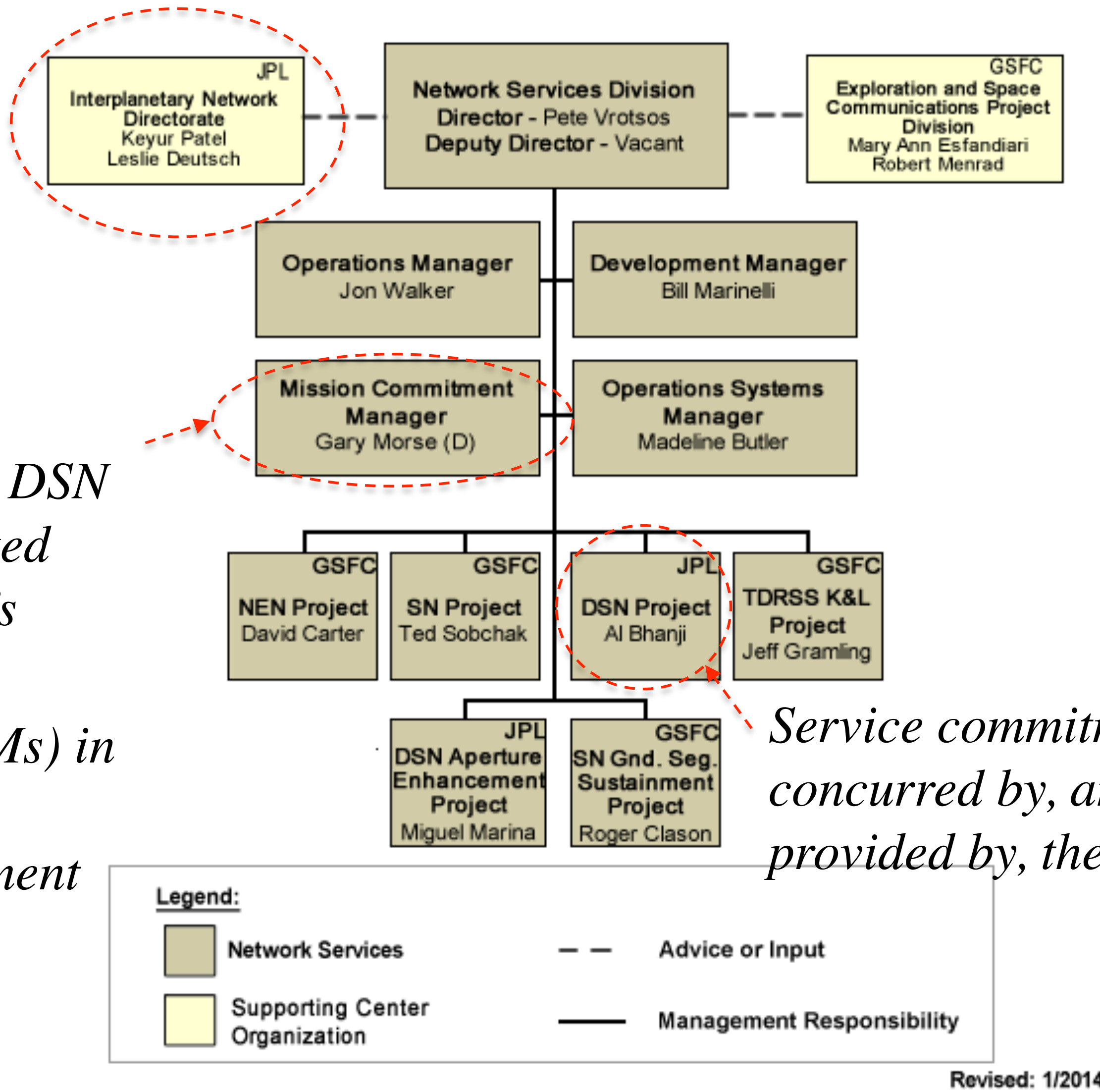
DSN Organizational Context (2/3)



DSN Organizational Context (3/3)

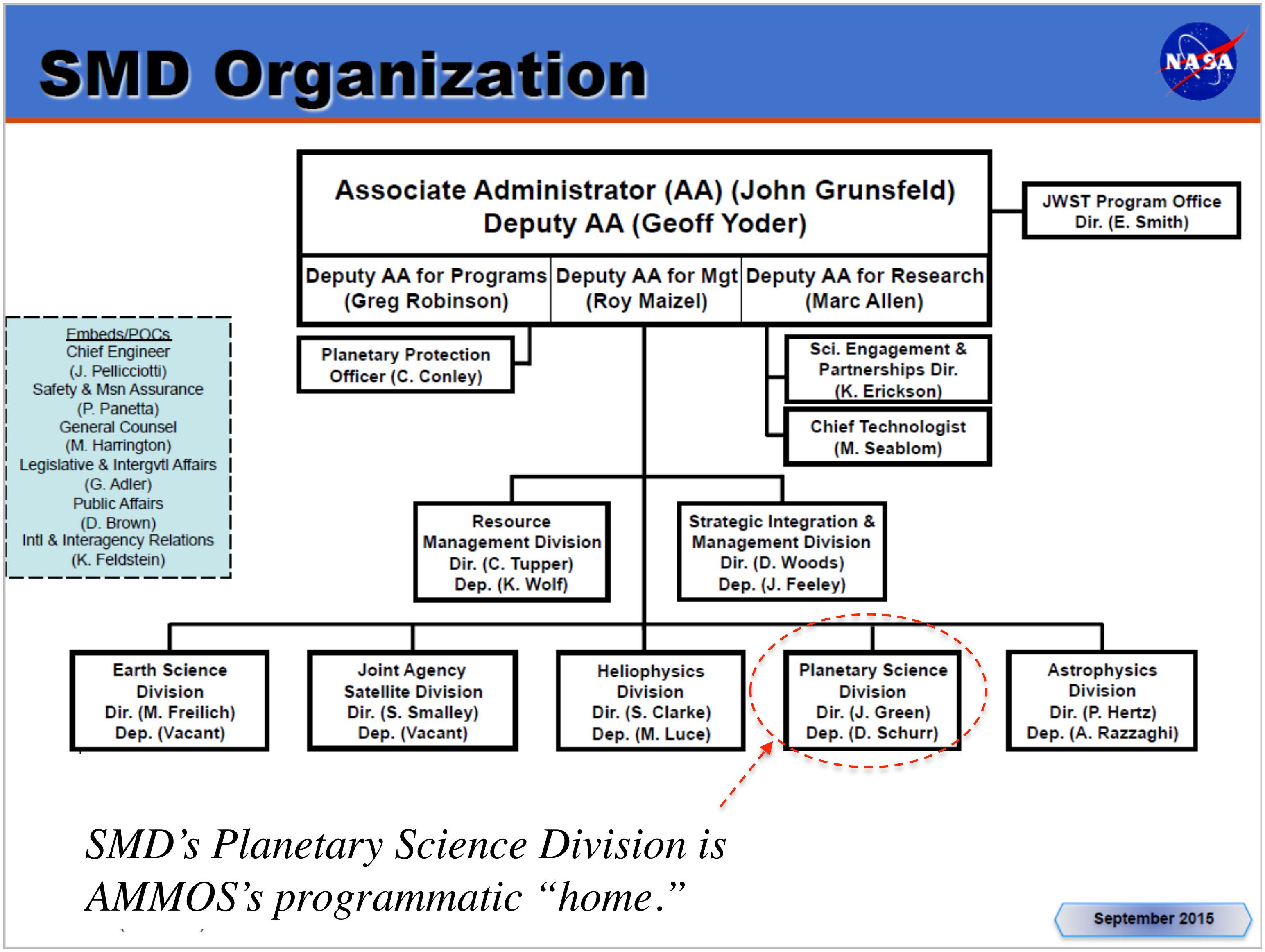
IND is JPL's "parent" organization for the DSN MIMs and DSN Project (among other things)

Commitments for DSN services are worked through the DSN's Mission Interface Managers (MIMs) in support of NSD's Mission Commitment Manager.



Service commitments are concurred by, and services are provided by, the DSN Project.

AMMOS Organizational Context (1/2)



AMMOS Organizational Context (2/2)

MGSS Program Office

Mission Directorate: Science Mission Directorate (SMD)
Division: Planetary Science Division (PSD)
Program: Advanced Multi-Mission Operations System (AMMOS)
Provider: Multi-Mission Ground Systems & Services Office (MGSS)
JPL "Parent" Organization: Interplanetary Network Directorate

Science Support:
AMMOS is a core set of reusable software and operations services that are adaptable for specific mission usage. Use of the AMMOS decreases the lifecycle cost and risk . Designed with NASA's science missions in mind, use of the AMMOS helps missions to achieve their science goals in today's budget-constrained environments.

Planetary Data System (PDS):
MGSS Manages the three PDS nodes at JPL. The Engineering Node providing systems engineering support across the entire PDS, Imaging Sub-Node maintains and distributes the archives of planetary image data acquired from NASA's flight projects, and the NAIF Node responsible for design and implementation of the SPICE concept.

Technical Capabilities:
The AMMOS product line provides most of the functions needed for a Mission Operations (aka Ground) System, including Navigation, Telemetry and Data Processing, Planning, Command and Sequencing, Configuration Management, DSN Scheduling, S/C Monitoring and Instrument Data Processing. A more complete list can be found in the AMMOS Catalog:
https://ammos.jpl.nasa.gov/toolsandservices/

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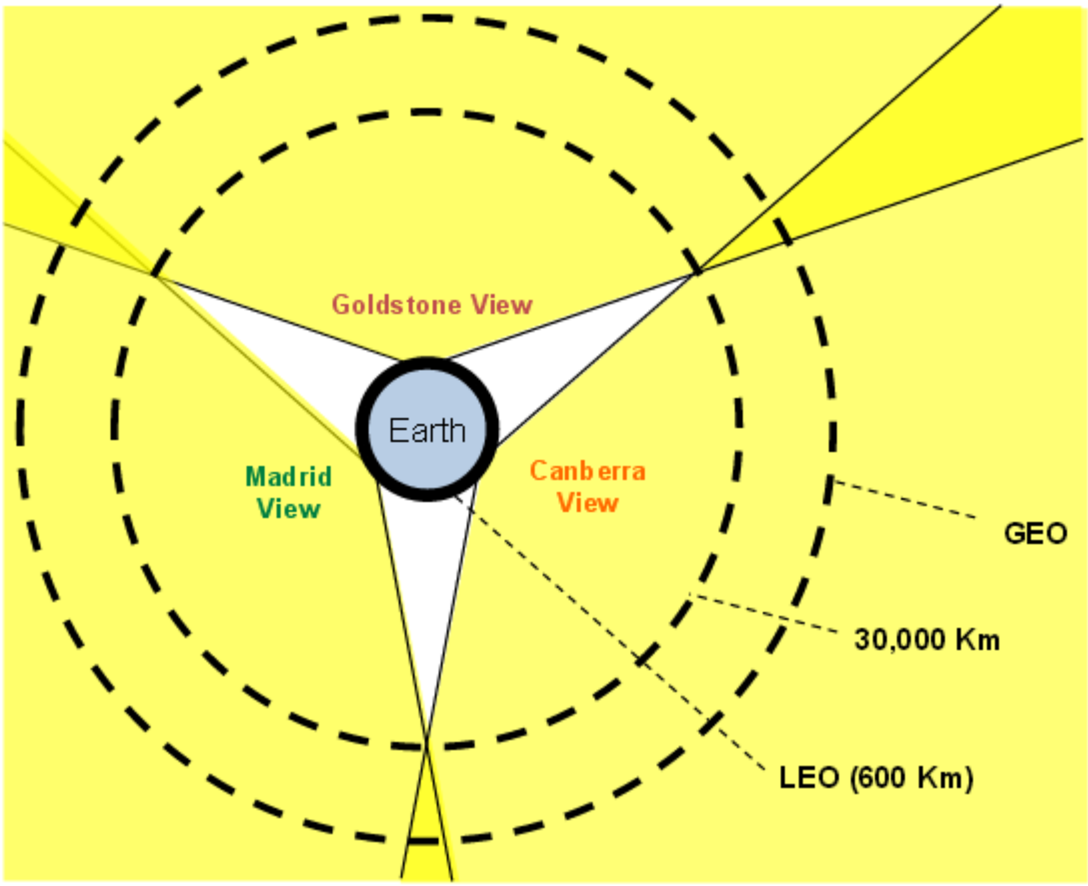
Deep Space: Operational View

Deep Space = Beyond GEO

Simplified DSN Visibility - looking down on the Earth's North Pole



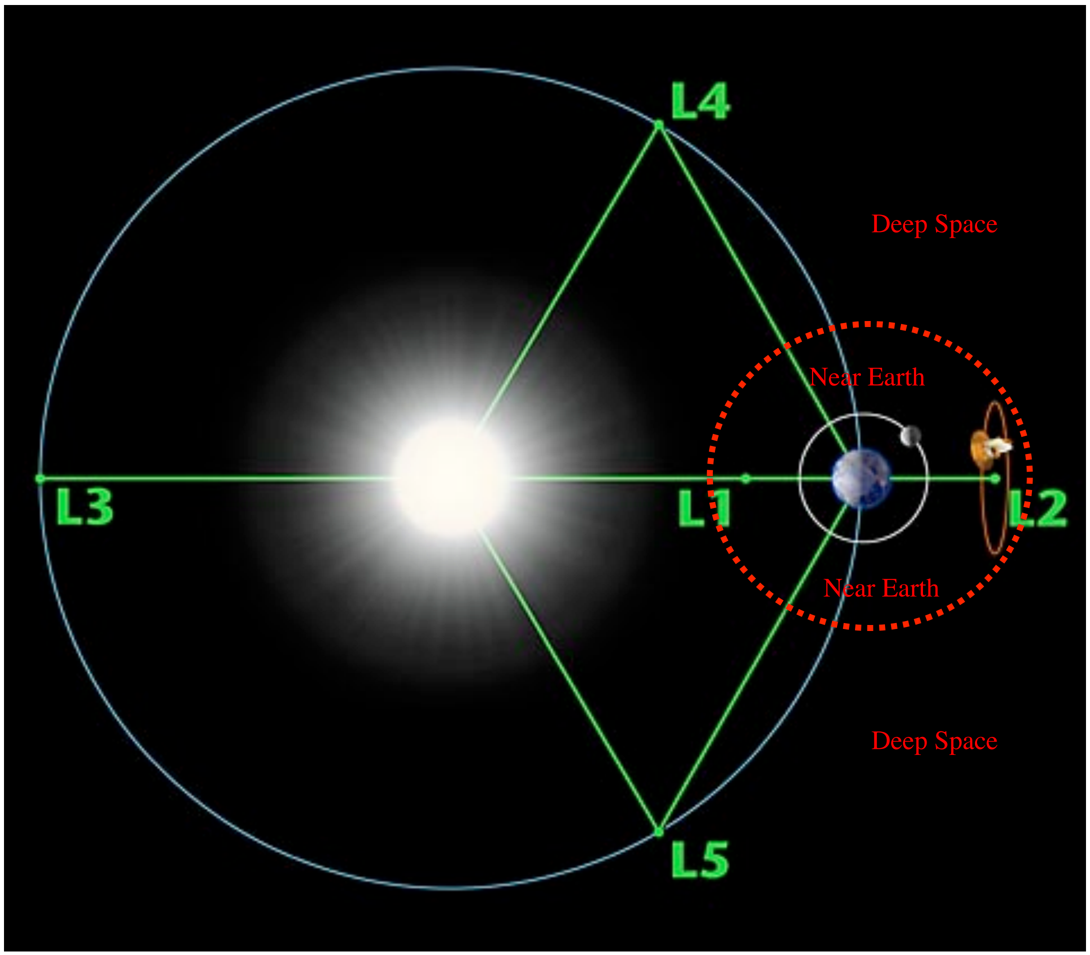
Suitability of ground antennas for beyond-GEO support depend, among other things, on:

1. Coverage
2. Gain
3. Receiver sensitivity
4. Effective Isotropic Radiated Power
5. Spacecraft-side G/T & EIRP

The DSN has been specifically engineered to have the coverage and capability needed to support missions beyond GEO.

Deep Space: Spectrum View

Deep Space = >2 million km from Earth



- Defined by International Telecommunications Union (ITU) to minimize interference with low-SNR planetary probes.
- Different frequency allocations apply depending upon whether the mission destination is within 2 million km or beyond.

Keep the dual definitions of "deep space" in mind as you plan for communications support.

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Key Personnel and Policy: Spectrum

- Obtaining a frequency assignment for a mission is a long-lead item. If you have not already started, start now.
- The process for obtaining a frequency assignment differs, depending upon whether your mission is NASA-sponsored or not.
- SCaN has appointed its Spectrum Management Division's Bill Horne as the initial spectrum POC for all cubesat missions. Bill can:
  - Determine whether application for frequency assignment should be worked through NTIA or the FCC.
  - Coordinate with the JPL Spectrum Manager, and for "near Earth" S-band the GSFC Spectrum Manager, for the spectrum engineering that identifies the optimal frequency assignment.
- For "near-Earth" missions, additional international and other government agency frequency coordination by the Spectrum Manager may be required. For "deep space" frequencies, JPL already has international coordination responsibility, somewhat simplifying the process.

The Spectrum Management briefing will provide frequency assignment process details and additional contact information.

Key Personnel and Policy: DSN/AMMOS

For DSN Service Coordination

Steve Waldherr and Glen Elliott, *Mission Interface Managers (MIMs)*

For AMMOS Service Coordination

Eleanor Basilio, *Commitments Pre-Phase A/Phase A*

The briefings by these POCs during the technical interchange will provide service commitment process details and additional contact information.

Key Personnel and Policy: Cross-Support

Any non-DSN Antenna Requirements

Steve Waldherr and Glen Elliott,
Mission Interface Managers (MIMs)

Sami Asmar, Manager of
Strategic Planning and
Cross-Support Agreements

Given that the DSN and its MIMs have extensive experience with deep space mission communication and radiometric tracking needs, non-DSN antenna support are to be sent through them to the cross-support manager.

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Class D vs. Class A

- By virtue of the budget they have available, Cubesats are generally regarded as Class D missions.
- As such, they assume greater risk and lower priority than Class A missions.
- Hence, supporting EM-1's primary mission will be the DSN's priority.

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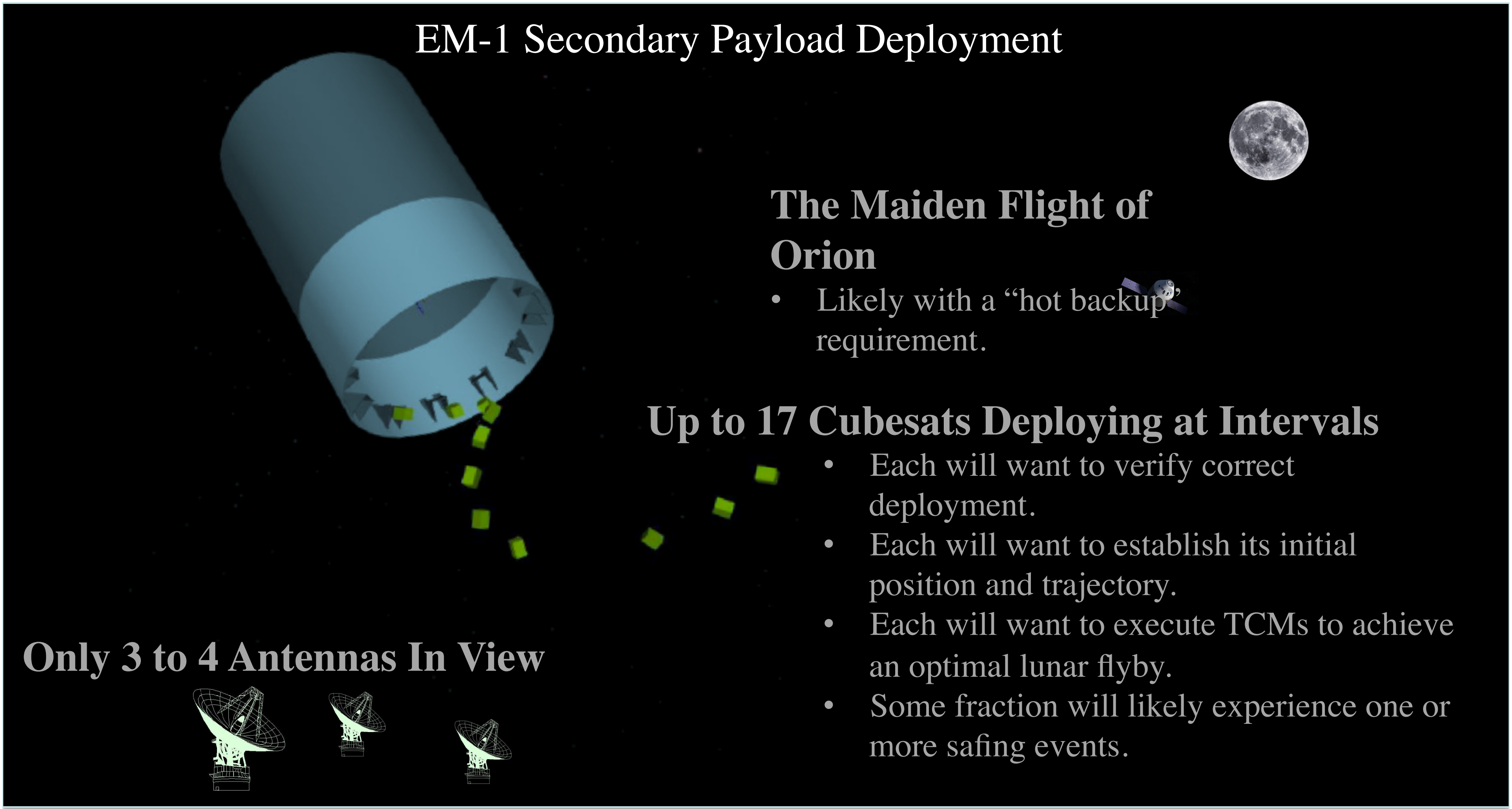
Strategy for CubeSats and the DSN

Doug Abraham

Topics

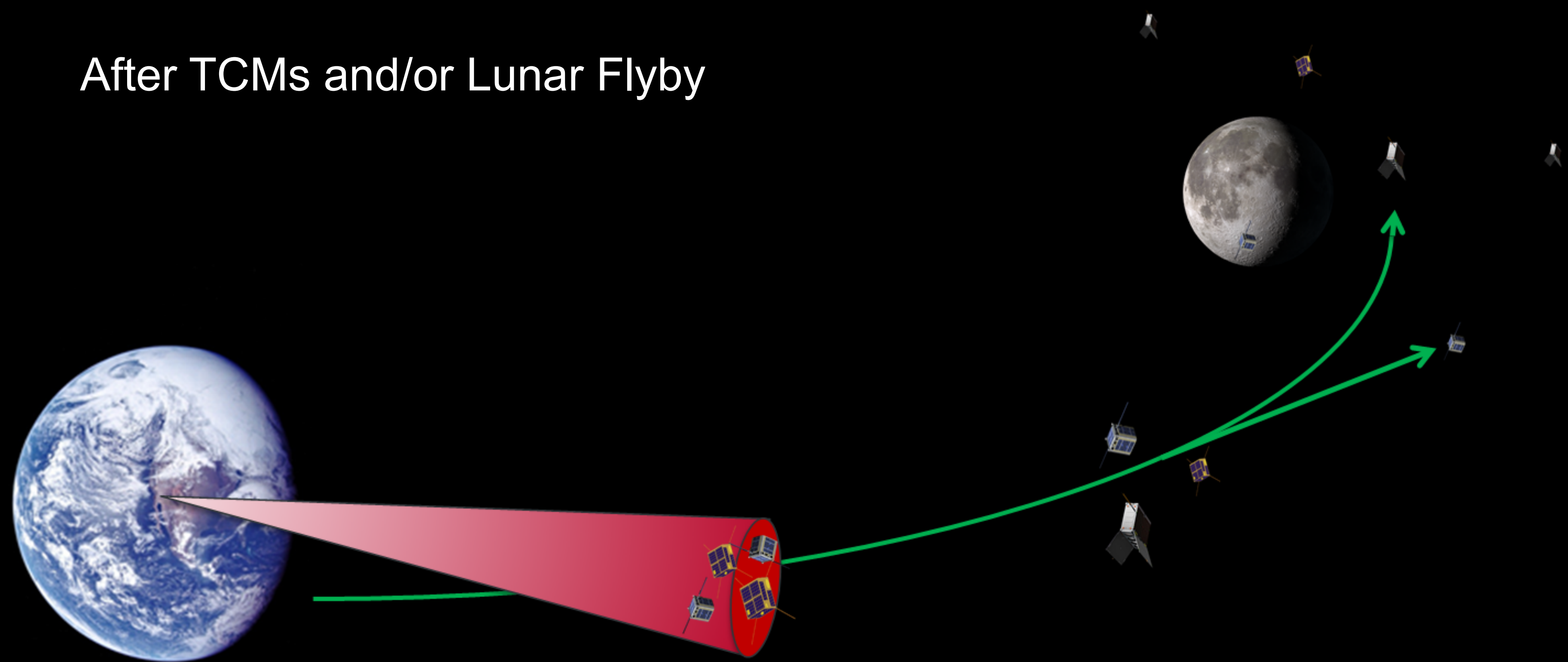
- The Challenges
- Strategy to Meet the Challenges
  - 4-MSPA
  - Serial Uplink Swapping
  - Large Antenna Cross Support
- Beyond 2018: Additional Techniques in Work
  - Opportunistic MSPA (OMSPA)
  - In-beam, Simultaneous, Multi-spacecraft Uplink
  - Less Uplink-Intensive Navigation
- Summary

Communications Challenge #1



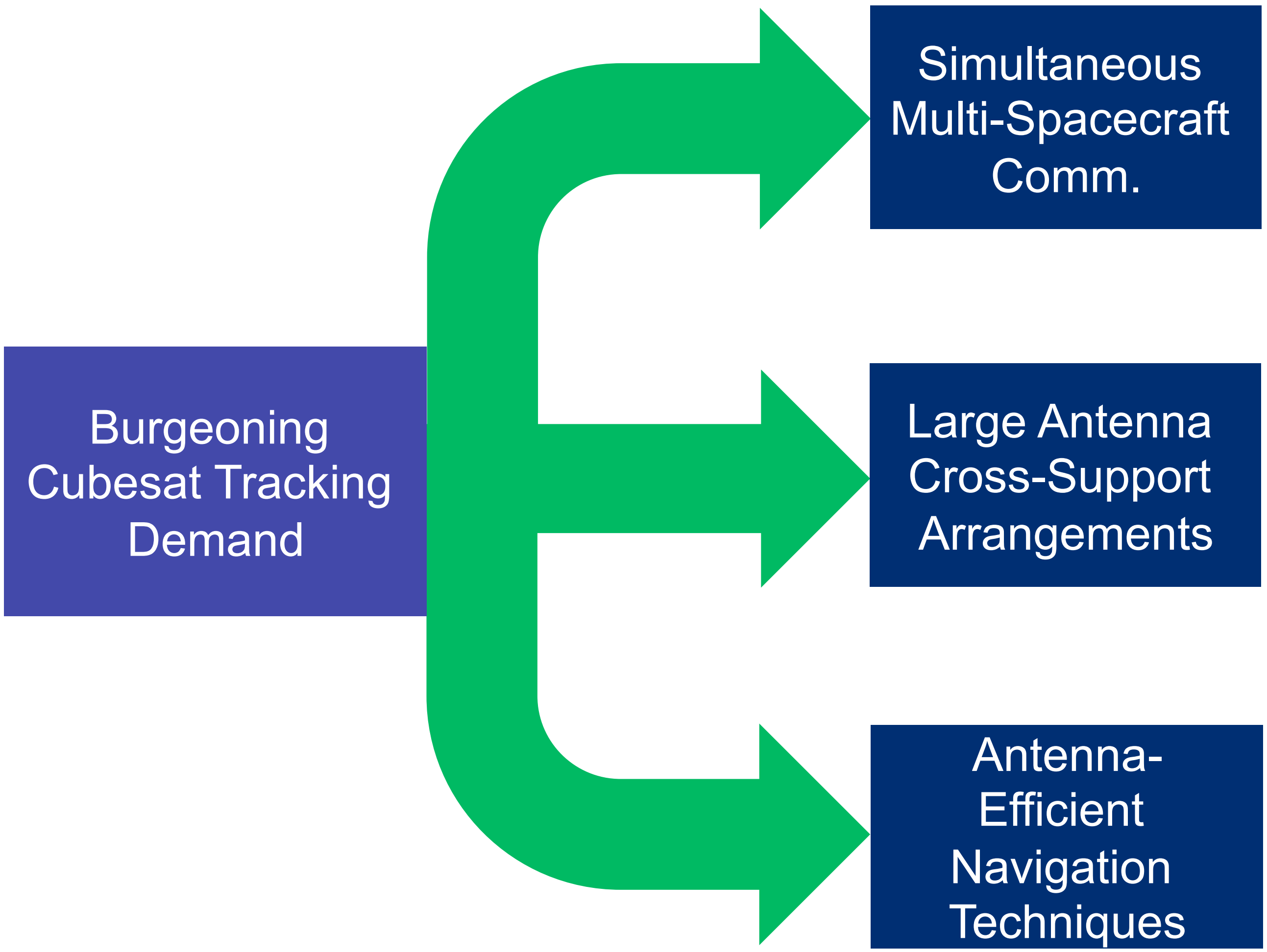
This is NOT a one-time challenge. Secondary payloads will become commonplace. What we do for EM-1 will set the tone for the future.

Communications Challenge #2



When EM-1's cubesats all go their separate ways, the overall number of DSN spacecraft supports will increase by ~30%.

Strategy to Meet the Challenges



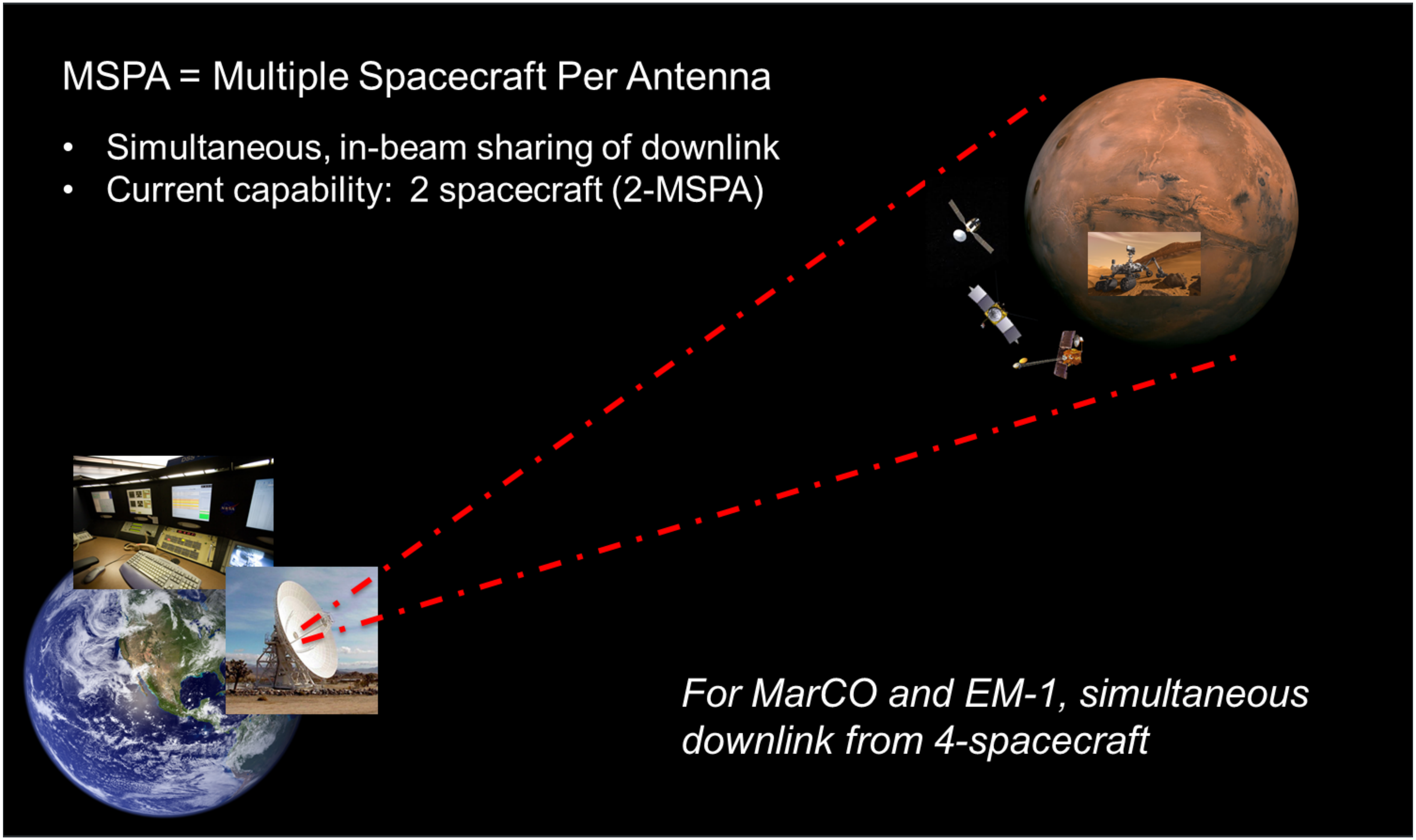
(EM-1 Critical)

- 4-MSPA
- Serial Uplink Swapping
- OMSPA
- Simultaneous Uplink

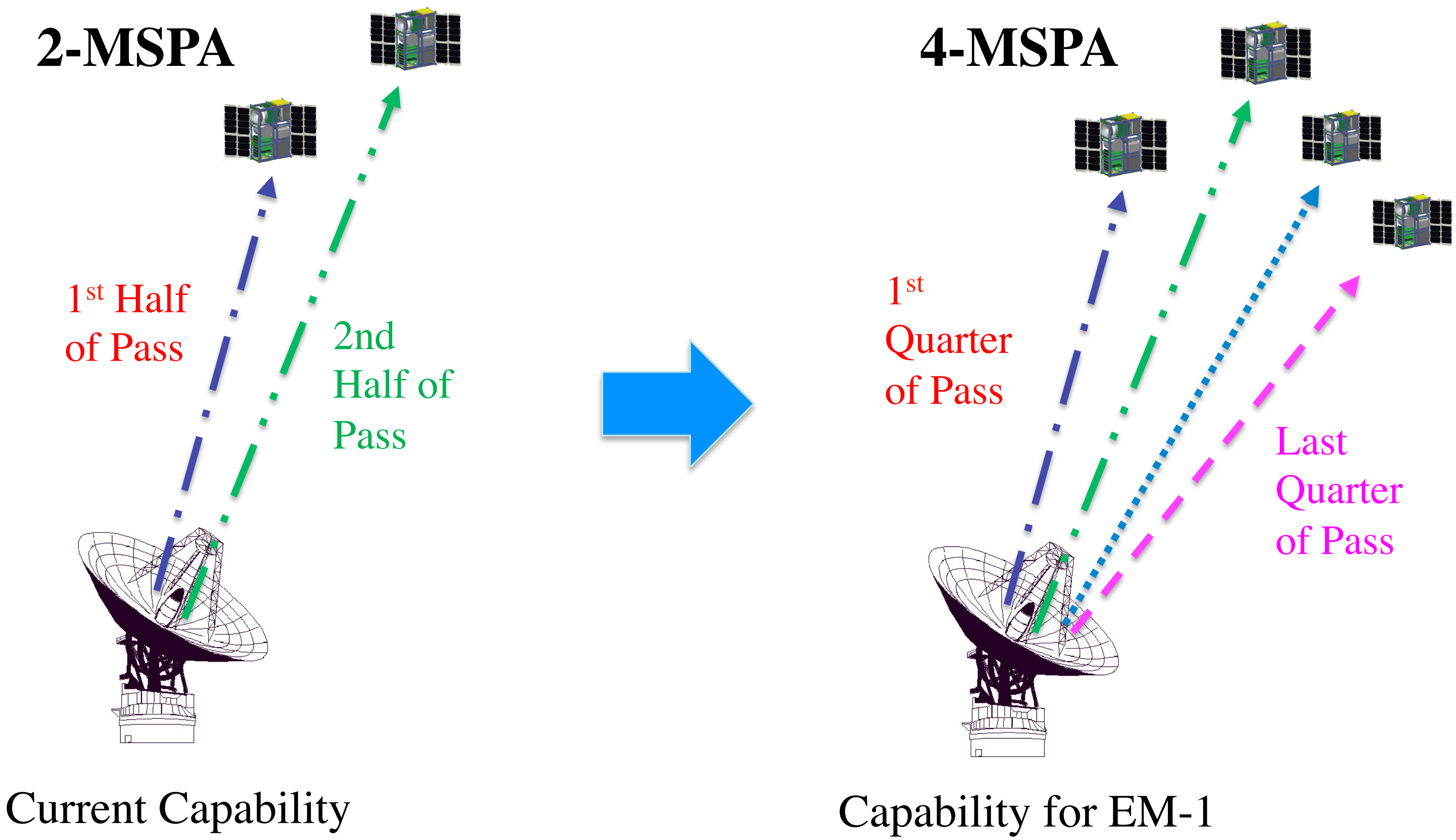
- MSU
- Other University
- ESA
- Other Foreign Agency

- Less Uplink-Intensive
- Non-NASA Augmentations
- Autonomous Onboard

4-MSPA


MSPA = Multiple Spacecraft Per Antenna
• Simultaneous, in-beam sharing of downlink
• Current capability: 2 spacecraft (2-MSPA)
For MarCO and EM-1, simultaneous downlink from 4-spacecraft

Serial Uplink Swapping

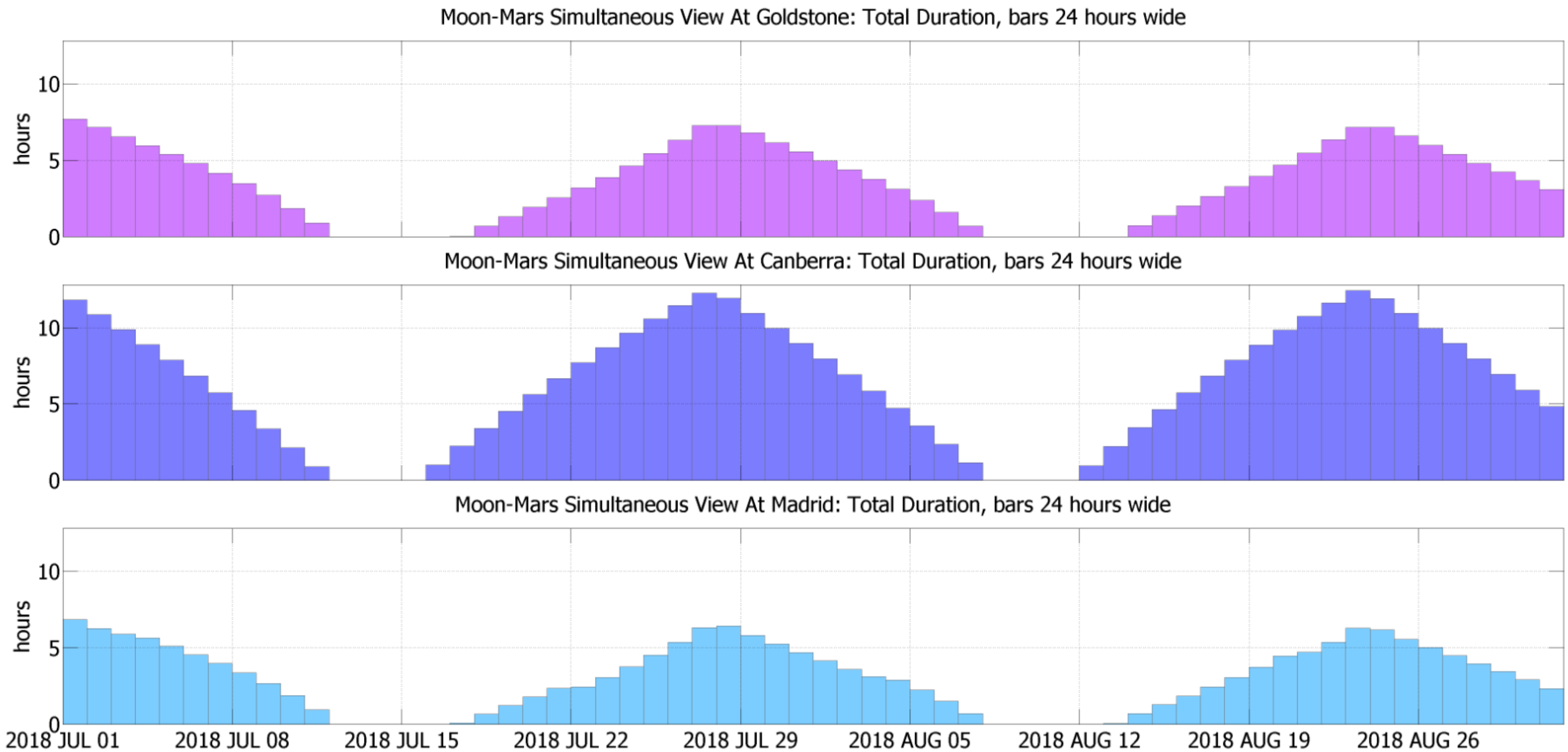


Allows each spacecraft some commanding and 2-way Doppler and ranging time during each 4-MSPA pass.

Some 4-MSPA Considerations

- Securing Proper Frequency Assignments
  - Want to avoid interference between cubesats/other spacecraft
  - Discussed in "IND Cross Support & Spectrum Management" briefing
- Understanding How Deployment Affects In-beam Time
  - Cubesat Deployment Analysis conducted to gain a preliminary understanding
  - Deployment velocity inversely related to in-beam time
  - Angular separation of deployed cubesats inversely related to in-beam time
  - Angle of cubesat deployment relative to antenna beam direction inversely proportional to in-beam time
  - Time between cubesat deployments inversely related to in-beam time
  - ICPS stability directly related to in-beam time
- Understanding Anomaly Response During 4-MSPA Support
  - Discussed in "DSN Engineering Approach and Anomaly Response"

After TCMs and/or Lunar Flyby

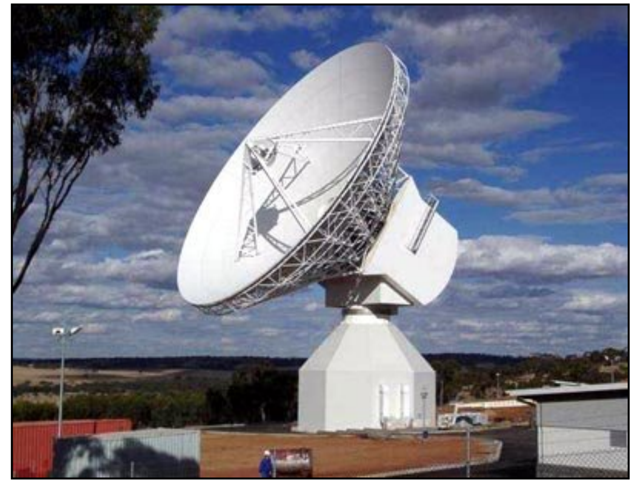


4-MSPA can still help by freeing up antennas focused on Mars spacecraft and temporarily diverting them to support individual cubesats during critical time periods. But, supplemental cross-support probably also needed.

Large Antenna Cross Support

Morehead State University 21m Station

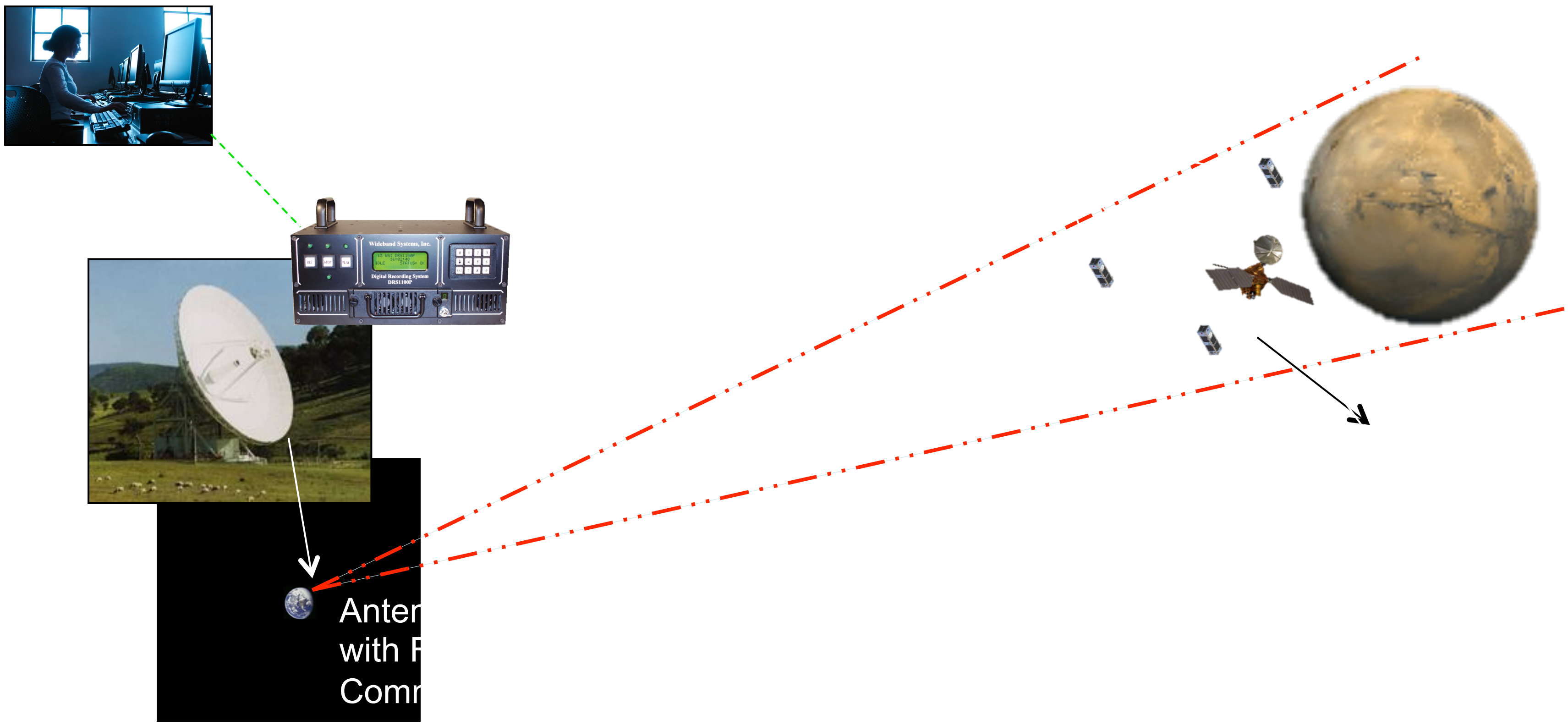
- MSU is the prototype for university cross-support in the U.S.
  - AES funding work to bring antenna up to DSN cross-support standards.
  - MSU's Lunar Ice Cube will be on EM-1.
- ESA cross-support agreements already exist.
  - Discussions with other countries currently in progress.



ESA 35m Stations

Other Stations

Your DSN MIM will coordinate supplemental cross-support for you as needed.



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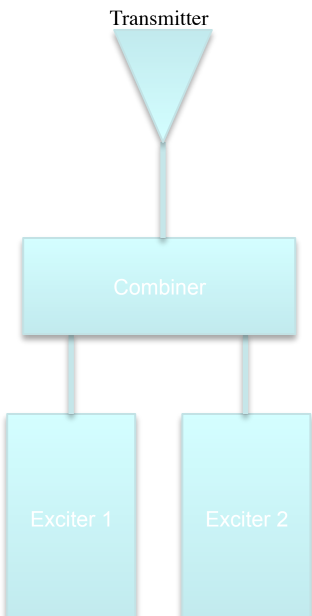
Beyond 2018: Additional Techniques (2/3)

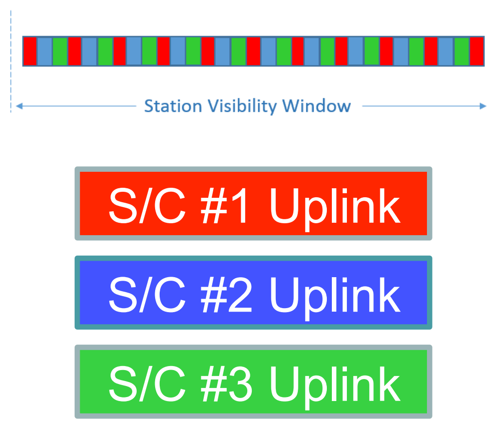
In-Beam, Simultaneous, Multi-Spacecraft Uplink

3 Techniques Under Investigation



Multiple Exciters
(Requires 80 kW tubes to reduce intermodulation effects)

Single Uplink with S/C ID Distinctions, Time Multiplexed



Single Frequency
(Requires some accommodation on spacecraft and coordination with other users)

Multiple Uplinks, Each on a Subcarrier Frequency

Subcarriers as Assigned Uplink Frequencies
(Requires coordinated spectrum assignments; multiple schemes with varying power and bandwidth efficiencies)

Beyond 2018: Additional Techniques (3/3)

Less Uplink-Intensive Navigation Techniques

One Example: One-Way Doppler Supplemented with delta-DOR via Non-DSN Assets

NAVIGATION WITH NONCOHERENT DATA:
A DEMONSTRATION FOR VEGA VENUS FLYBY PHASE

88-4262-CP

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and
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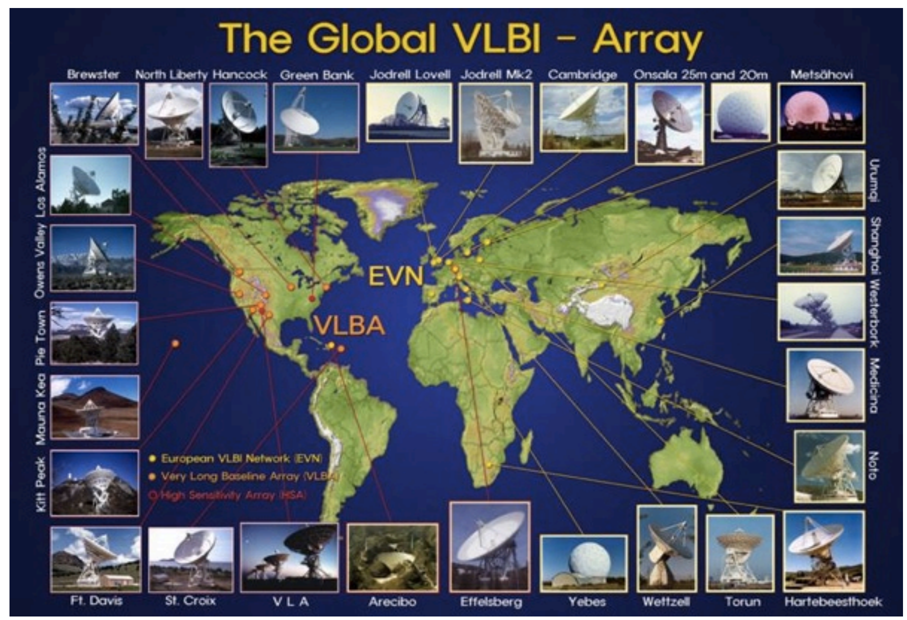
Abstract

Deep Space navigation with noncoherent (one-way) data types is demonstrated for the VEGA Venus flyby phase under extreme conditions. Estimates and statistics are computed using one-way Doppler and wideband Very Long Baseline Interferometry (VLBI) data. The behaviour of the onboard oscillator is modeled for both spacecraft to obtain useful orbit determination results. Even with this limitation, it is demonstrated that one-way data solutions are comparable with the solutions using both Soviet sparse coherent (two-way) and wideband VLBI data. During the useful life time of VEGA balloons, the two solutions differ by a maximum of 4.7 km in position and 7.6 cm/sec in velocity for VEGA 1 and by a maximum of 8 km and 42 cm/sec for VEGA 2.

I. Introduction

dial and range rate components. One-way Doppler also provides similar information with relatively less accuracy. This has raised the possibility of navigating future spacecraft primarily with one-way data only. This scenario would expand the use of listen-only antennas and subsequently reduce the dependence on two-way tracking. The use of one-way data strategy may become important for outer planet missions as the round trip light time limits the amount of two-way Doppler which may be recorded at a single station. It is necessary to demonstrate the navigation capability of a one-way data strategy for various phases of a mission before applying this techinique for Deep Space navigation. Several studies were conducted and are in progress to evaluate the performance of one-way data strategies for different phases of an interplanetary spacecraft mission (Ref. 1).

In December 1984, two identical Soviet VEGA spacecraft were launched with the dual objectives of



Summary

- **We have a 3-pronged strategy for meeting the burgeoning cubesat demand.**
  - For EM-1: 4-MSPA, Serial Uplink Swapping, and Large Antenna Cross Support
  - For beyond 2018, additional techniques include: Opportunistic MPSA, Simultaneous Multi-spacecraft Uplink, and Less Uplink-Intensive Navigation.
- **For 4-MSPA and Serial Uplink Swapping be sure to:**
  - Secure your frequency assignments
  - Understand the deployment factors that will maximize in-beam time
  - Understand anomaly response while supported in 4-MSPA mode
- **For Large Antenna Cross-Support**
  - Your DSN Mission MIM will coordinate supplemental cross-support for you as needed.

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DSN Approach and Anomaly Response

Jeff Berner

Agenda

- DSN CubeSat / SmallSat policies
  - Preparation
  - Launch
  - Post-launch
- DSN Toolbox

Assumptions

1. EM-1 launch requires one prime & one backup 34m antennas
2. Only one 34m antenna available for cubesat initial acquisition
3. Cubesat release may occur at up to 4 different “bus stops”
4. Funding for 4-MSPA and Uplink Swaps is provided by SCaN

Preparation (1 of 2)

- New DSN readiness review: *Small-Sat Event Readiness Review*
  - Similar but less formal than Mission Event Readiness Review (MERR)
  - Held around the same time as the MERR for the main mission launch (e.g., EM-1)
  - Covers all DSN-supported Small Sats on the launch vehicle
  - Reviews support time sequence from one Small Sat to another
- Compatibility testing
  - As of now, DSN-spacecraft compatibility testing is a necessity
  - Only one test is needed; timing based on transponder heritage
- DSN will work with other agencies / organizations for cross support during launch, if feasible

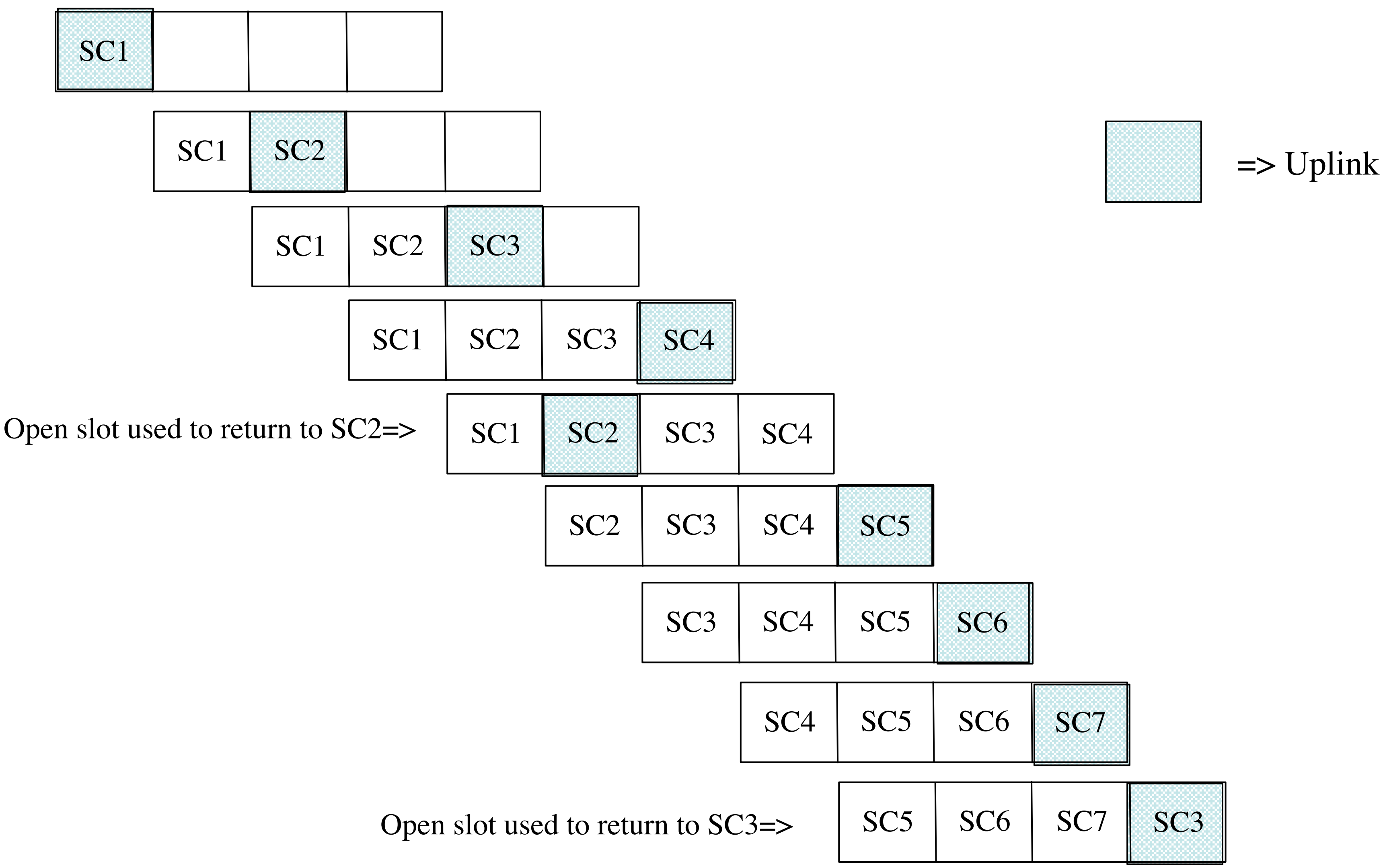
Preparation (2 of 2)

- Key is determining the acquisition, tracking, and handover timing
  - Assumes one antenna available for tracking
  - Assumes 4 Multiple Spacecraft per Aperture (4-MSPA) and uplink swapping
    - Four downlinks at a time, one uplink at a time
- Although Small Sats are independent missions, we all have to work together to optimize the tracking availability
  - Resources have to be shared among all spacecraft
- A timeline of the support sharing will be developed
  - Need to understand the needs of each spacecraft (e.g., how long before needing a command, how long before needing 2-way Doppler, etc.)
  - Mission Interface Manager (MIM) will be the point of contact for this information

Launch & Initial Acquisition

- Each “bus stop” release cycle will be treated as a critical event
  - First one is during the time frame of EM-1 initial acquisition, so only one 34m antenna will be available for cubesat tracking
  - Other bus stops may not align with EM-1 view, so there might be more resources available
- Due to the number of missions and the resource usage, the DSN will need to follow the planned sequence
  - Sequence will have been developed to optimize resources and mission needs (e.g., commanding, spacecraft health, Doppler)
  - If possible, time slots for dealing with potential spacecraft issues will be allocated
- If a mission has an issue (e.g., delayed acquisition), DSN will have to move on to the next mission, even if problem is not resolved
  - After initial sequencing through the cubesats, DSN can work with the missions to reprioritize tracking schedule
  - If unused time slots available, they can be used to resolve issues
  - Spacecraft should design to survive lack of early contact

Conceptual Tracking Sequence



Post Launch

- Post initial acquisition, cubesats will be treated like other missions
- Missions that can use MSPA (e.g., missions going to the moon) will be encouraged to do so
- Can sign up for Emergency Control Center (ECC) support
  - Provides limited services in the event of damage to JPL DSOC (e.g., earthquake)
  - Requires mission commitment and support, so may not be desirable to low cost missions
- DSN will classify cubesat key events as Level 3 support levels
  - Provides additional NOPE support
  - By definition, cubesats are Class D, high risk missions
- Cubesats can declare spacecraft emergency, but initial DSN response will only affect other cubesat scheduled passes
  - Can negotiate with other missions for tracking time to support recovery effort, but not guaranteed response

DSN "Toolbox"

- 4-MSPA
  - Track 4 spacecraft at a time if they are in antenna beamwidth
- Uplink swapping
  - Swap uplink from one spacecraft to another, to another, …
  - Requires time in between each uplink to reconfigure
- Non-standard turn around ratios
  - If different spacecraft go to different targets (e.g., moon and asteroid), they could share the same uplink frequency, and use a different downlink frequency (different turn around ratio)
  - Enables two spacecraft to have the uplink at the same time
    - Spacecraft would have to check spacecraft number in the command data to ensure correct command usage

Conclusion

- DSN is looking at ways to simplify the process for cubesats and looking at ways to optimize resource usage and maximize data return
- We understand that all the missions are independent, but we need to work together to effectively use the resources

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Spectrum Management

Farzin Manshadi & Feiming Morgan

Introduction

- Use of the radio spectrum for all spacecraft is governed by rules and regulations established by national and international organizations
  - The International Telecommunication Union (ITU) makes spectrum allocations for all radio communication services internationally
    - A United Nations organization

  - In the United State frequency spectrum rules are governed by the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA)
    - FCC governs the rules for commercial, state, and local government organizations
    - NTIA governs the rules for federal government agencies
    - FCC and NTIA publish their own rules and tables of frequency allocations

  - NASA policy requires that use of the spectrum be compliant with the ITU and NTIA Tables of Frequency Allocations, and rules and recommendations established by ITU, NTIA, and Space Frequency Coordination Group (SFCG)
    - SFCG is sanctioned by ITU
    - Most space agencies are members of SFCG

Frequency Authorization

- All U.S. missions need to obtain authorization (license) for their frequencies from NTIA or FCC to be able to operate with those frequencies
  - Even if one uplink is used for commanding multiple mission, each mission requires a separate authorization for their uplink frequency
  - Authorization is contingent upon compliance with all NTIA and FCC rules and regulations as well as successful coordination with all other missions

Major Steps for JPL Missions' Frequency Selection and Authorization

- Band use consultations during the proposal phase or pre-phase A
- Frequency selection/recommendation Studies
- Pre-coordination within NASA and with DoD/DOC
- Pre-coordination with foreign space agencies (ES/JAXA, SFCG)
- NTIA System Reviews
  - 4 stages but typically for CubeSats we just file for Stage 4 due to time constraints
    - Stage 1 (Conceptual)
    - Stage 2 (Experimental)
    - Stage 3 (Developmental)
    - Stage 4 (Operational)
- Official frequency authorization and assignment is issued by NTIA
- It takes at least 2 years for frequency selection, coordination, and authorization
  - If only Stage 4 is filed it takes at least 2 months for frequency selection and 1 year for coordination and NTIA authorization

Frequency Coordination

- All selected frequencies should be pre-coordinated with other users of the band to avoid interference and the need for operational coordination after launch
  - Domestically, all JPL frequencies are pre-coordinated with other NASA centers, DoD, and DoC (NOAA) domestically
  - Internationally, JPL frequencies are pre-coordinated through the SFCG with space agencies
  - Operational coordination must be avoided as much as possible
  - Because JPL selects frequencies for almost all deep space missions, no pre-coordination is necessary for deep space frequencies
    - JPL will also predict and mitigate any potential interference for all deep space missions during their lifetime
- Internationally, all missions have to notify ITU and coordinate with other administrations
- The process for both domestic and international frequency authorization and coordination is time consuming

Frequency Selection for Deep Space Missions

- JPL, as NASA's deep space expert, participates in ITU and SFCG
- SFCG Administrative Resolution 21-1 resolves that all space agencies get assistance from JPL for selection of frequencies for their deep space missions
  - ITU defines "deep space" to be a region that it more than 2 million km away from the Earth
  - JPL has selected deep space frequencies for all other NASA centers, ESA, JAXA, RFSA since 2001
  - JPL ensures that interference to deep space missions is minimized through out their primary operational period
  - Coordination is automatic and no international coordination is needed
    - ITU notification is still needed
  - It is recommended that non-Government agencies that operate CubeSats either follow SFCG Res A 21-1 or coordinate their deep space frequencies with JPL
    - NASA HQ approval is needed for frequency selection

Near-Earth Missions Frequency Selection Process

- Missions contact the the spectrum manager as early as possible in their initial design phase
- Missions will provide the orbital parameters, telecom parameters, and critical event periods to the spectrum manager
- Spectrum Engineering analyzes mission data and will select one or several frequencies that potentially will be acceptable by other users of the band
  - For near-Earth S-band, GSFC can select the frequencies for JPL
- JPL Spectrum Manager contacts NASA GSFC Spectrum Office for its approval
- If GSFC approves, JPL Spectrum Manager coordinates with DoD and DoC spectrum managers for their approval
- If DoD approves JPL Spectrum Manager presents the selection to ESA and JAXA for their approval
- The frequencies are presented to the SFCG
- Spectrum Manager/Alternate Spectrum Manager submits frequency authorization applications to NTIA
  - Several iterations may be necessary before final approval from the NTIA
- Stage 4 approval will authorize space operation for the mission

Spectrum Management for CubeSats

- The spectrum management for CubeSats is more complicated than most major space systems
  - Change of telecom and orbital parameters and launch date is very common with CubeSats as the mission is developed
  - Mix of commercial (university affiliation) and Government resources makes use of Government bands more complicated
    - It is important to establish who is paying for and who is controlling the spacecraft
  - Frequency selection, coordination, and authorization has to follow the same process as any other flight mission (as shown in previous pages)
    - The process is not compatible with the fast and cheap nature of CubeSats
    - CubeSats can cause harmful interfere like any other flight system
    - No dedicated frequency band for CubeSats
    - Use of Amateur Radio bands is prohibited by NASA
  - It is recommended that non-Government agencies that operate CubeSats either follow SFCG Res A 21-1 or coordinate their deep space frequencies with JPL

Major Space Research or Earth Exploration Frequency Allocations

- S-band
  - 2025-2110 MHz uplink, near-Earth
  - 2110-2120 MHz uplink, deep space*
  - 2200-2290 MHz downlink, near-Earth
  - 2290-2300 MHz downlink, deep space
- X-band
  - 7145-7190 MHz uplink, deep space
  - 7190-7235 MHz uplink, near-Earth
  - 8025-8400 MHz downlink, near-Earth (Earth Exploration only)
  - 8400-8450 MHz downlink, deep space
  - 8450-8500 MHz downlink, near-Earth,
- Ka-band
  - 25.5-27.0 GHz downlink, near-Earth and deep space**
  - 34.2-34.7 GHz uplink, deep space
  - 31.8-32.3 GHz downlink, deep space
  - 40.0-40.5 GHz uplink, near-Earth and deep space
  - 37.0-38.0 GHz downlink, near-Earth and deep space

* Not available in Spain

** NASA intents to keep this band for use by near-Earth missions only (no deep space missions in this band)

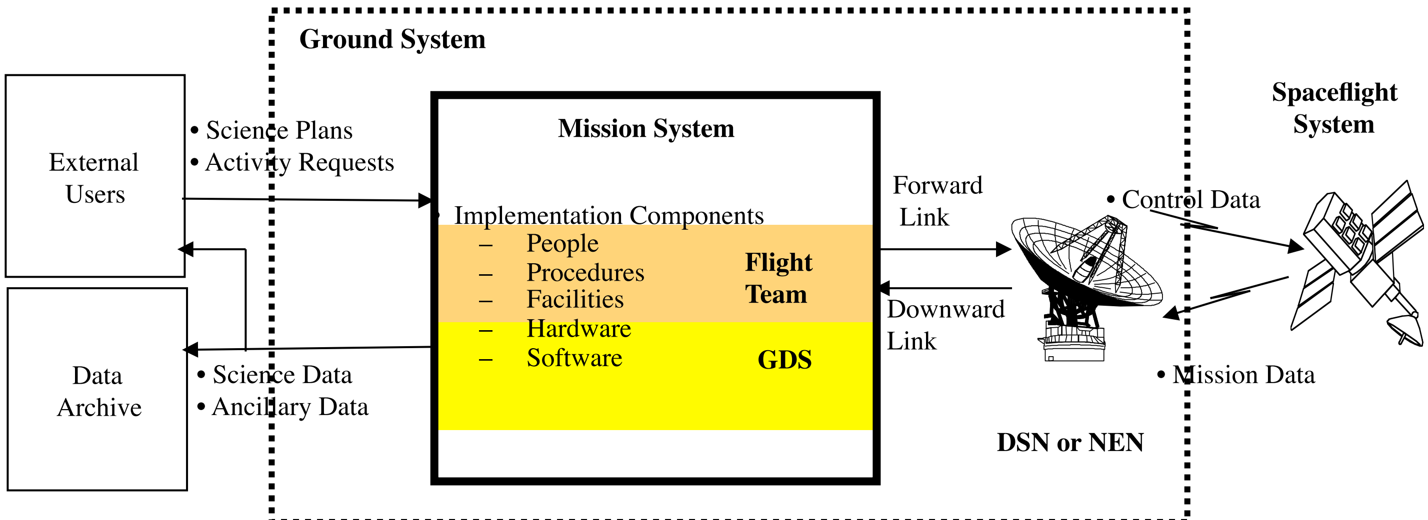
IND Cubesat Briefing/Technical Exchange
10 November 2015

Jet Propulsion Laboratory
California Institute of Technology

Mission System Overview

Eleanor Basilio

Mission System Overview

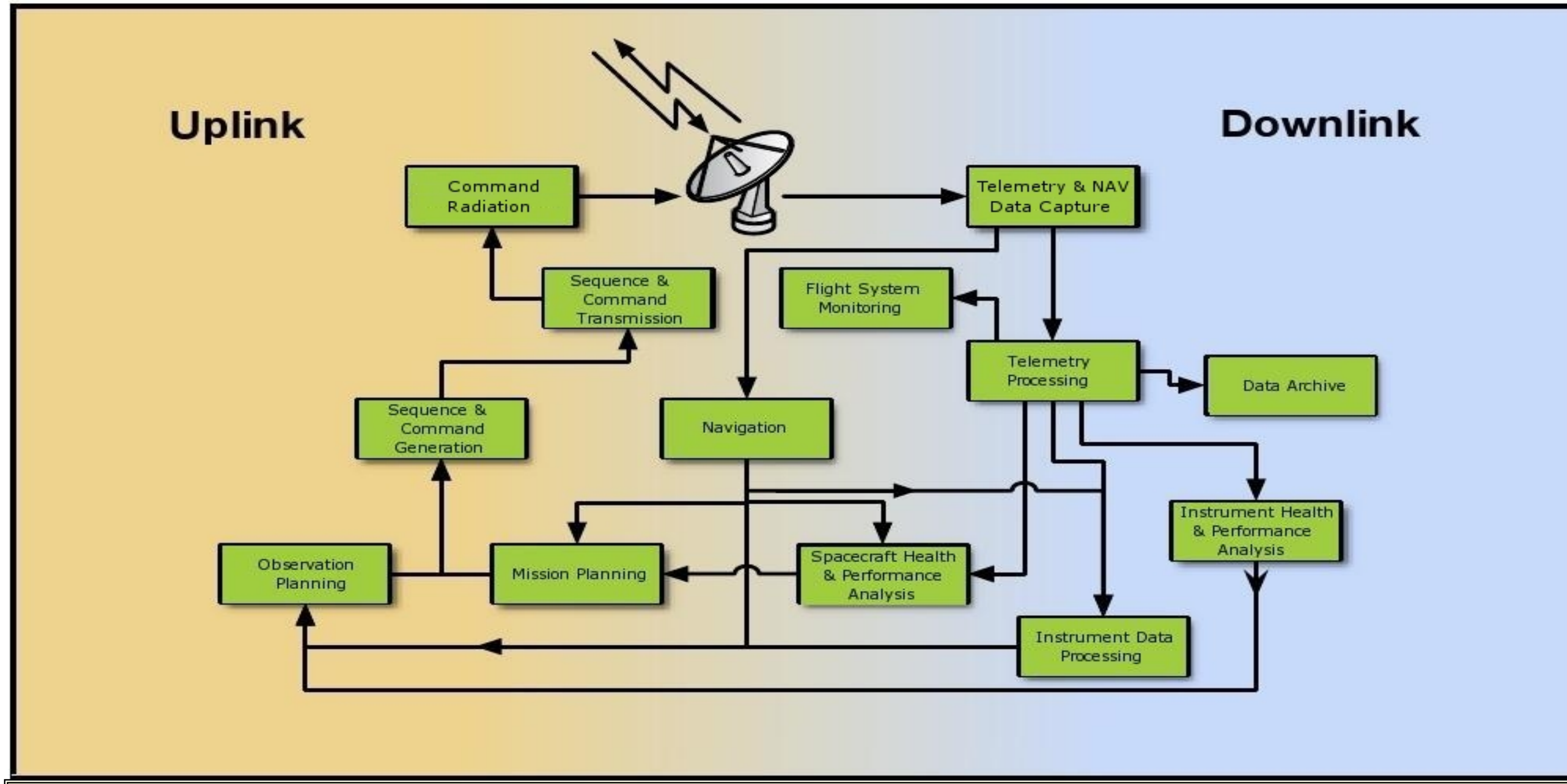


What is MGSS? And What is AMMOS?

- Product: Advanced Multi-Mission Operations System (AMMOS)
  - This is the part of the Mission System that is the core multi-mission set of hardware and software (aka multi-mission GDS)

- Organization: Multi-mission Ground Systems and Support Program Office (MGSS)
  - This is the organization that manages the multi-mission GDS

A typical decomposition of a Mission System into Functional Elements



The AMMOS is based upon a simple idea: For those elements of mission operations systems that are common to multiple projects, build them once rather than duplicating that development and maintenance effort for each project

ICAP (Interplanetary Customer Assistance Package)

OUR RECOMMENDATION FOR SMALLSATS

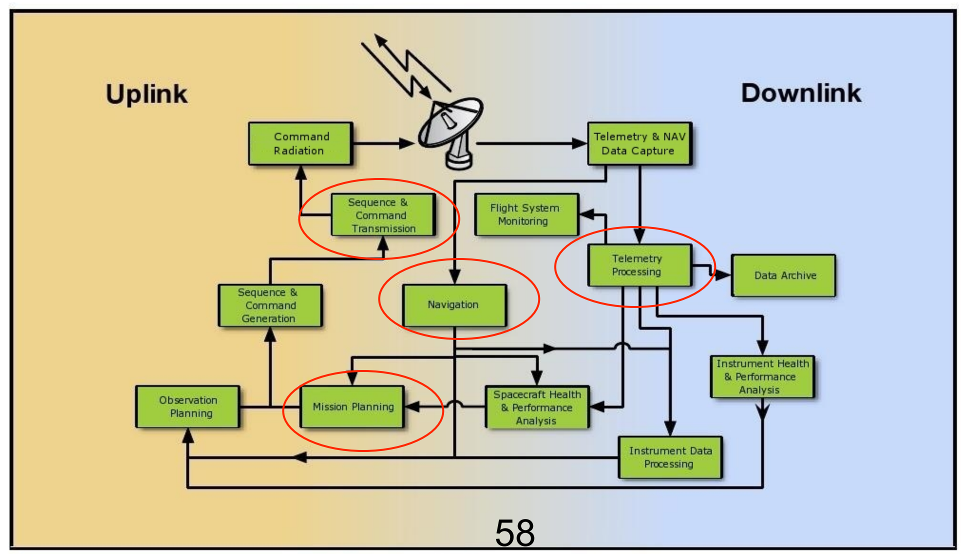
What is an ICAP?

ICAP = IND Customer Assistance Package

- A low cost method for JPL to support multiple low cost missions.
- Will enable a (small spacecraft) ground system engineer to install a command/telemetry system that will meet the project needs with minimal MGSS involvement that will lead to lower cost
- Will consist of selected:
  - AMMOS tools/services and description
  - User's guide

AMMOS Tools/Services Available for Smallsats

- Tools
  - Command Sequence Generator (aka MPS Editor)
  - AMMOS Mission Data Processing and Control System (aka AMPCS)
- Services
  - Navigation
  - DSN scheduling



Our Customer Base: Missions to which we Build

- Are those smallsat missions that plan to use the DSN (e.g planetary, heliophysics, astrophysics, lunar, etc.)
- Are those missions that comply with standards (e.g. CCSDS Version 2 tlm frame, XTCE)
- Are those missions for which the uplink will include SLE protocol (CLTU data format)
- Are those missions that agree that the mission adaptations will be done by the scripting agents, not the core AMMOS software

Summary of MGSS Business Model

- *MGSS will* provide an integrated cmd/tlm tool and sequencing tool to the missions
- *MGSS will* provide documentation pertinent to the software (e.g. user's guide, standards, installation guide, troubleshooting guide, software interface specs, cmd/tlm dictionary templates, etc.)
  - MGSS will provide "AMMOS 101" to expedite customer configuration with minimal hand-holding
- *MGSS will* provide a wiki site (future plans) to accommodate questions, share ideas, transfer of info, lessons learned, and FAQs. Wiki site will be open to customers only, as a community of users.
  - Outside of JPL firewall; currently unsupported
- *MGSS's* ICAP package is at no cost to the project
  - MGSS will provide (8) hours of consulting service for the ICAP package at no cost to the mission
- *MGSS will* provide optional services as requested by the missions at a nominal fee[1]
  - Navigation and Mission Design, DSN scheduling, Training, Relay services, Consultation
  - Additional systems engineering for advanced AMPCS capabilities
  - We are not currently providing MSA facility as a service
- Ground system deployment is the responsibility of the mission
- Procurement of hardware is the responsibility of the mission

[1] Contact the MGSS Mission Interface Office to get a preliminary cost estimate

Who Do I Contact?

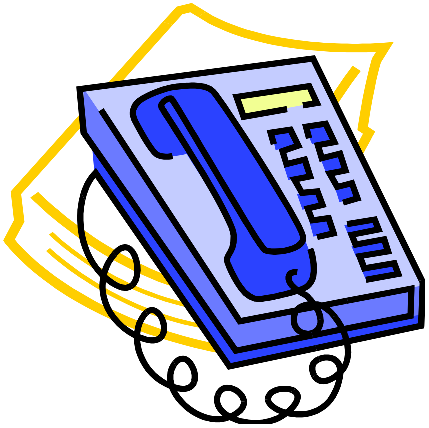
- For AMMOS tools/services, please call or email:

  MGSS Mission Interface & Commitments Office

  Eleanor Basilio 818-393-0686, ebasilio@jpl.nasa.gov

  Greg Welz 818-393-4978, gwelz@jpl.nasa.gov

- Or go to http://ammos.jpl.nasa.gov for an overview of AMMOS



An MGSS Service, Presented by Tomas Martin-Mur

MISSION DESIGN AND NAVIGATION

Summary of MDNAV Services

- MDNAV Services include:
  - Provision of the hardware, software, data, people, processes, and facilities required for the design of efficient routes for a spacecraft to a desired Solar System destination
  - Safely piloting spacecraft to that destination
- JPL MDNAV is already providing these services for NEA Scout and Lunar Flashlight
- Primary functions involved are the design, analysis, and reconstruction of trajectories and maneuvers
- Costs and accuracies for MDNAV Services will be based on numerous factors, including the mission phase in which the service is started, mission duration, objectives, constraints, destination, propulsion, complexity, critical events, tracking data requirements, etc.

An MGSS Service, Presented by Karen Yetter

DSN SCHEDULING

MRSS: Who We Are and What We Do

- Who We Are
  - MRSS Team has extensive experience in the planning and negotiation of Deep Space Network (DSN) resources.
  - 12 member team supporting 20 missions, representing a wide range of projects (NASA and Non-NASA) and mission types. Including the first interplanetary CubeSat to use the DSN, MarCO.
- What We Do: Coordinate, Schedule, and Negotiate DSN Resources
  - Coordinate mission subsystem level requirements into one integrated mission tracking strategy, including collaboration with project elements to provide solutions to technical and engineering problems related to DSN scheduling
  - Represent the project in the DSN negotiation process: Maintain tracking requirements, provide solutions for conflict resolution, and keep project aware of any potential or real constraints for DSN tracking resources.
  - Distribute tracking information to project in support of operational planning.
  - Continuous monitoring of DSN resources scheduled. 24/7 support if needed.

Benefits of Our Services to SmallSats

- DSN Scheduling
  - DSN is an oversubscribed resource. Contention levels for antenna resources can range from 30% – 70%. Active participation in the negotiation process is key to ensure requirements are met.
  - Negotiation process requires constant monitoring, schedule deadlines are fluid. Rapid response required in all negotiation phases.
  - Dynamic tracking OPS schedule: Scheduled tracks are susceptible to impact by other users and DSN at any time.
- MRSS Support
  - MRSS brings vast knowledge and experience in project scheduling, ability to work with projects to find best fit for obtaining DSN resources.
  - Cross-trained team, no single point of failure.
  - We are multi-mission dedicated DSN scheduling team, ability to provide continuous DSN schedule monitoring and negotiation on a part-time budget.
  - Ability to bring experience gained from representing MarCO cubesats.

SmallSat Operations: Cost Effective Options for DSN Scheduling

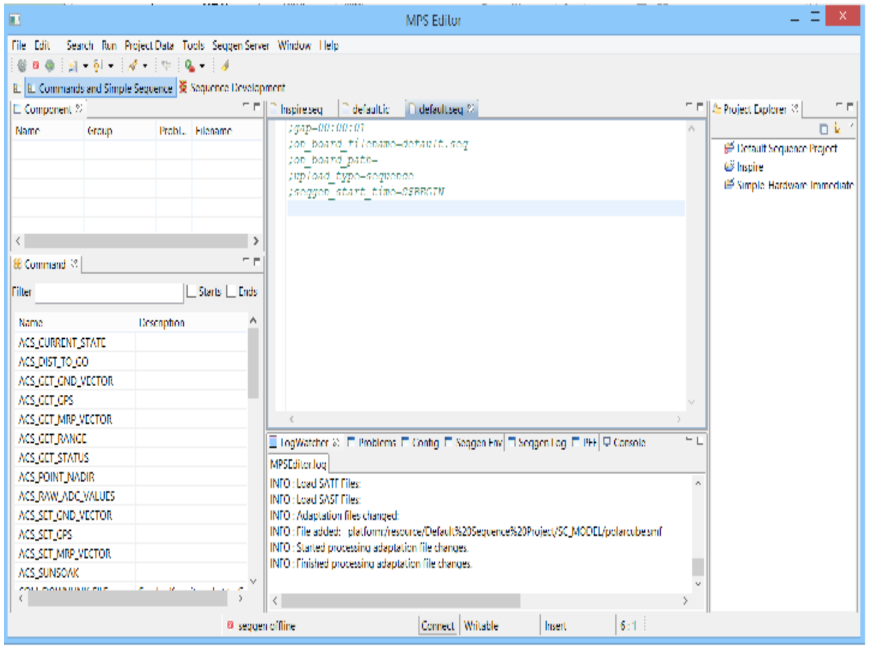
- Options to Help Reduce Cost
  - Development phase: MRSS participation as needed.
  - Operations Phase E: Full participation delayed until Launch - 8 months. DSN requires input of DSN tracking requirements at 6 months prior to track.
  - Use existing MRSS procedures and products (heritage)
  - DSN Tracking Requirement Planning: Tracking request and time spent in negotiation = dollars. To help reduce cost:
    - Reduce tracking profile to minimal acceptable level: Includes track length, number of tracks, and antenna type.
    - Maintain tracking requirements consistent with forecast.
    - Maximize flexibility/Minimize constraints: Easier to schedule and more likely for project to meet operational/ data return requirements.
  - MRSS support scalable, room for creativity
    - Remove/reduce some services and products. Example: MRSS negotiate and monitor tracking only, no product deliveries. Project pull DSN coverage from DSN.

An MGSS Tool, Presented by Barbara Streiffert

MPS (MISSION PLANNING & SEQUENCING) EDITOR

MPS Editor

Context Sensitive Editor for Command Sequence Generation



MPS Editor
Command Sequence Generation

- Automatic import of command database
- Command sequence perspective
  - Allows drag and drop of commands
  - Checks command parameters against definition for number, type and range
  - Allows for command parameters that are signed and unsigned integers, floats, strings, times, durations, enumerated types
  - Allows relative or absolute timing as well as gaps for relative timing
  - Allows for specification of on-board file name
- Capability to communicate with and start external process for command translation or other purposes automatically
- Configuration file input for one-time adaptation

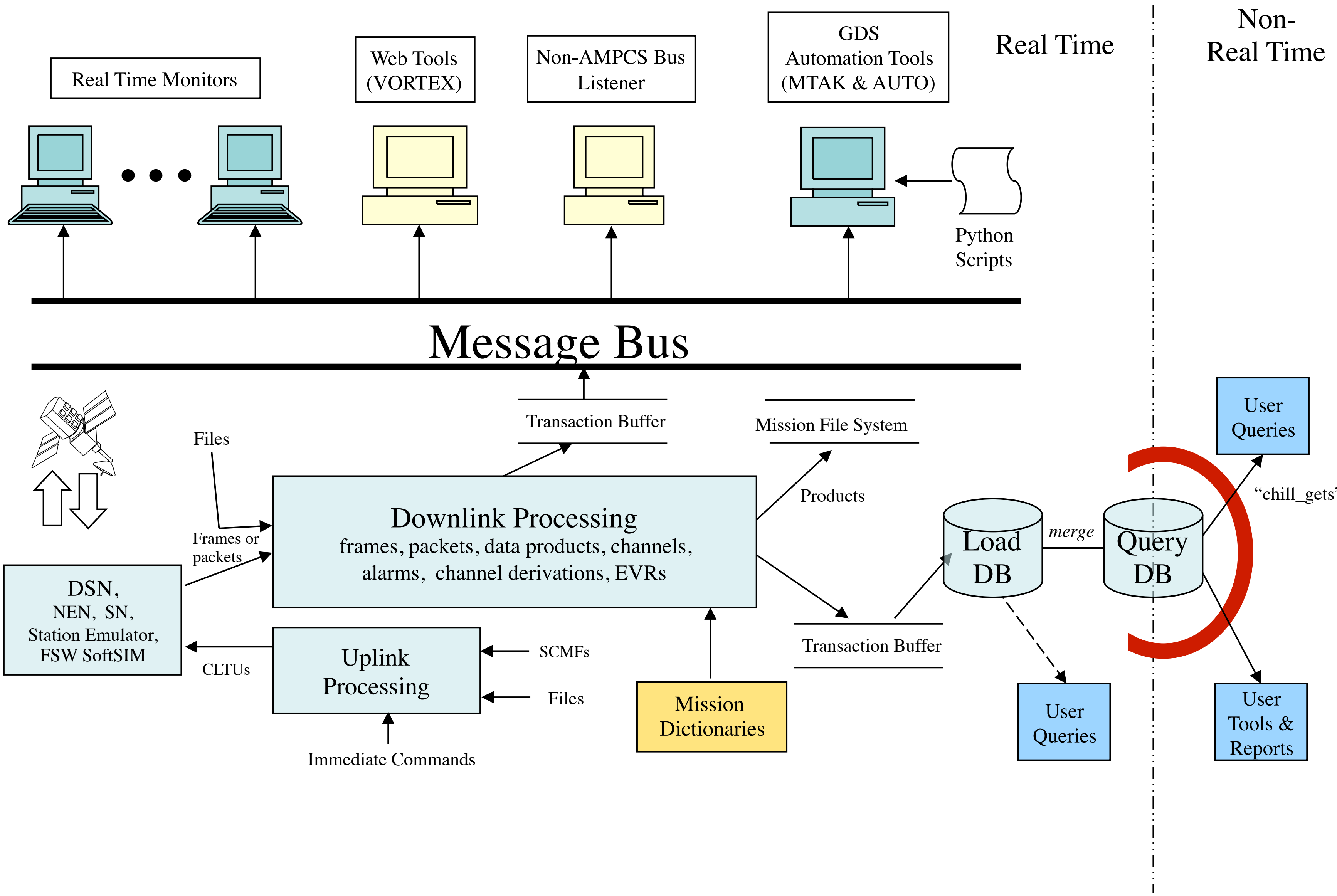
An MGSS Tool, Presented by Dave Santo

AMPCS (AMMOS MISSION DATA PROCESSING AND CONTROL SYSTEM)

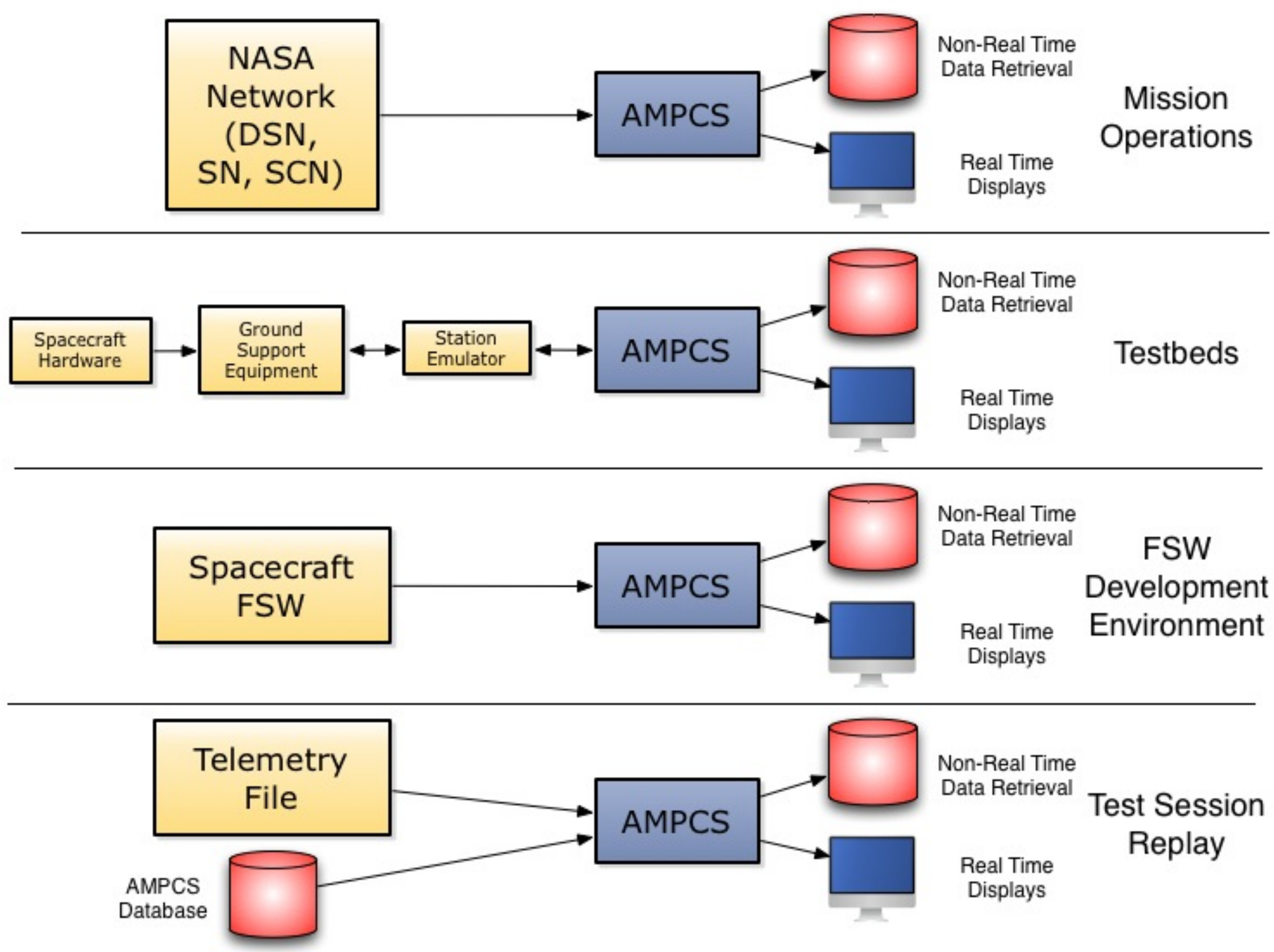
What is AMPCS?

- **Flexible, full function, real-time Mission Control application**
  - Flexible deployment model: from a single linux laptop, to multi-node hardware
  - Dictionary-driven (binary data formats, channel and EVR definitions, alarm definitions, derived channel definitions)
  - Supports both telemetry processing and commanding; provides realtime displays; performs ground-derived channel derivation; supports custom (Java) mission-provided derivation algorithms
  - All input, processed data, logs, messages, etc is stored, and can be queried
  - During FSW Development, Testbed and ATLO operations: test tool for flight software development, spacecraft integration and test
  - During Operations: operational system for spacecraft telemetry processing and monitoring
- **Accepts CCSDS formatted in-sync frames and/or packets**
  - Sources: DSN, NEN/SN, a station emulator, simple ground support equipment, files
  - Processes frames and/or packets into telemetry products (channelized data, EVRs, Products, etc.) for delivery to real time and non-real-time users
- **Testbed and ATLO Telemetry Environments**
  - "Test session" concept organizes access to each test's pertinent data
    - Captures all incoming and processed data, logs, FSW version used, and dictionary version used, etc.
    - Allows cross-test session analysis
  - Specialized test environment features to assist spacecraft integration and test (e.g. command fault injection, test session management, frame/packet watch displays, frame quality displays)
  - (A)MPCS Test Automation Toolkit (MTAK) for spacecraft test scripting (session dependent)
- **Extensive command line queries and tools, python scripting environment**
  - AMPCS Utility Toolkit for Operations (AUTO) for lights-out operations automation (session independent)

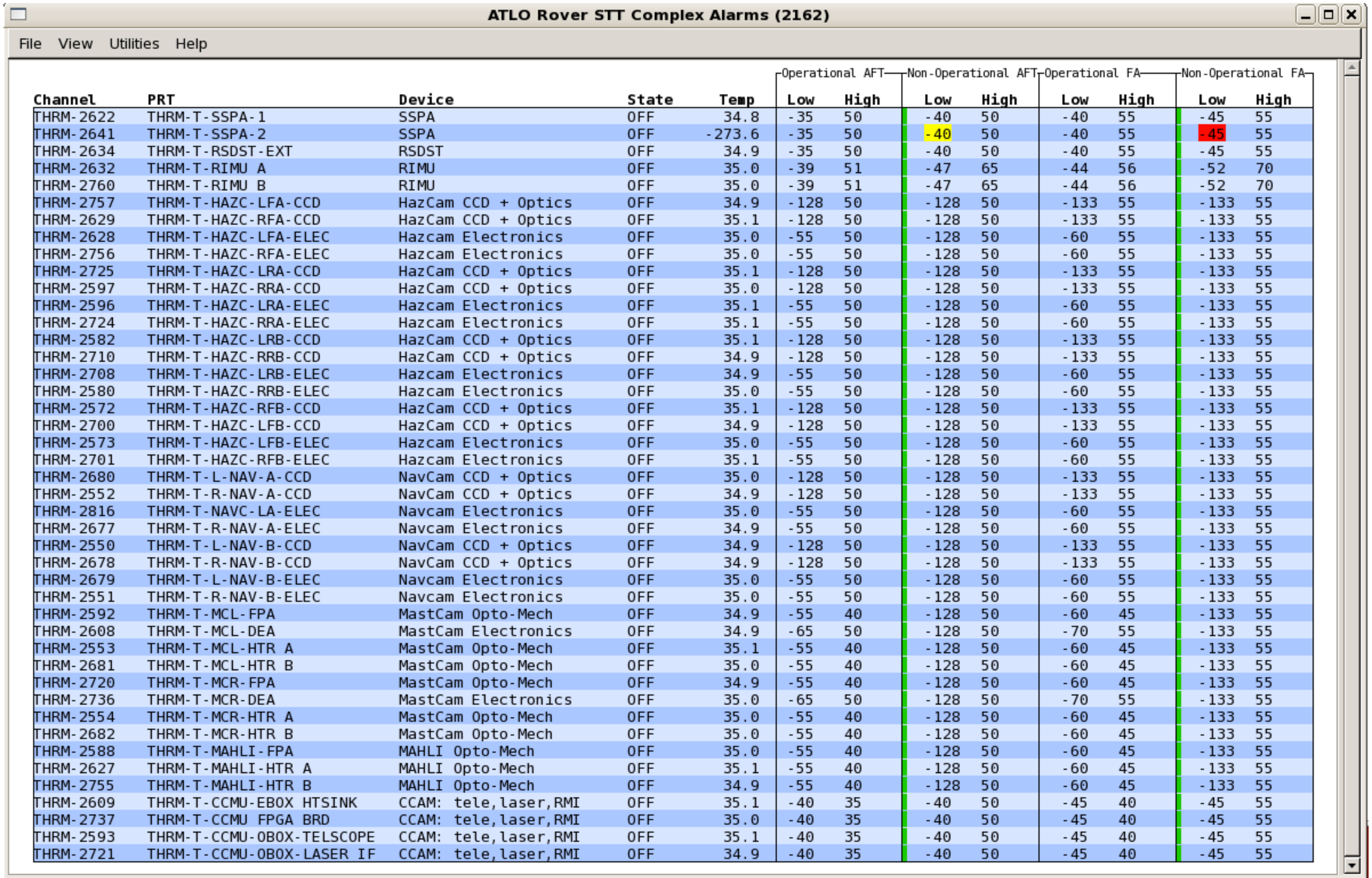
AMPCS System Architecture



Venue Support for "Test As You Fly"



Example Display (fixed page)



ATLO Rover STT Complex Alarms (2162)

File View Utilities Help

Channel	PRT	Device	State	Temp	Operational AFT Low	Operational AFT High	Non-Operational AFT Low	Non-Operational AFT High	Operational FA Low	Operational FA High	Non-Operational FA Low	Non-Operational FA High
THRM-2622	THRM-T-SSPA-1	SSPA	OFF	34.8	-35	50	-40	50	-40	55	-45	55
THRM-2641	THRM-T-SSPA-2	SSPA	OFF	-273.6	-35	50	-40	50	-40	55	-45	55
THRM-2634	THRM-T-RSDST-EXT	RSDST	OFF	34.9	-35	50	-40	50	-40	55	-45	55
THRM-2632	THRM-T-RIMU A	RIMU	OFF	35.0	-39	51	-47	65	-44	56	-52	70
THRM-2760	THRM-T-RIMU B	RIMU	OFF	35.0	-39	51	-47	65	-44	56	-52	70
THRM-2757	THRM-T-HAZC-LFA-CCD	HazCam CCD + Optics	OFF	34.9	-128	50	-128	50	-133	55	-133	55
THRM-2629	THRM-T-HAZC-RFA-CCD	HazCam CCD + Optics	OFF	35.1	-128	50	-128	50	-133	55	-133	55
THRM-2628	THRM-T-HAZC-LFA-ELEC	Hazcam Electronics	OFF	35.0	-55	50	-128	50	-60	55	-133	55
THRM-2756	THRM-T-HAZC-RFA-ELEC	Hazcam Electronics	OFF	35.0	-55	50	-128	50	-60	55	-133	55
THRM-2725	THRM-T-HAZC-LRA-CCD	HazCam CCD + Optics	OFF	35.1	-128	50	-128	50	-133	55	-133	55
THRM-2597	THRM-T-HAZC-RRA-CCD	HazCam CCD + Optics	OFF	35.0	-128	50	-128	50	-133	55	-133	55
THRM-2596	THRM-T-HAZC-LRA-ELEC	Hazcam Electronics	OFF	35.1	-55	50	-128	50	-60	55	-133	55
THRM-2724	THRM-T-HAZC-RRA-ELEC	Hazcam Electronics	OFF	35.1	-55	50	-128	50	-60	55	-133	55
THRM-2582	THRM-T-HAZC-LRB-CCD	HazCam CCD + Optics	OFF	35.1	-128	50	-128	50	-133	55	-133	55
THRM-2710	THRM-T-HAZC-RRB-CCD	HazCam CCD + Optics	OFF	34.9	-128	50	-128	50	-133	55	-133	55
THRM-2708	THRM-T-HAZC-LRB-ELEC	Hazcam Electronics	OFF	34.9	-55	50	-128	50	-60	55	-133	55
THRM-2580	THRM-T-HAZC-RRB-ELEC	Hazcam Electronics	OFF	35.0	-55	50	-128	50	-60	55	-133	55
THRM-2572	THRM-T-HAZC-RFB-CCD	HazCam CCD + Optics	OFF	35.1	-128	50	-128	50	-133	55	-133	55
THRM-2700	THRM-T-HAZC-LFB-CCD	HazCam CCD + Optics	OFF	34.9	-128	50	-128	50	-133	55	-133	55
THRM-2573	THRM-T-HAZC-LFB-ELEC	Hazcam Electronics	OFF	35.0	-55	50	-128	50	-60	55	-133	55
THRM-2701	THRM-T-HAZC-RFB-ELEC	Hazcam Electronics	OFF	35.1	-55	50	-128	50	-60	55	-133	55
THRM-2680	THRM-T-L-NAV-A-CCD	NavCam CCD + Optics	OFF	35.0	-128	50	-128	50	-133	55	-133	55
THRM-2552	THRM-T-R-NAV-A-CCD	NavCam CCD + Optics	OFF	34.9	-128	50	-128	50	-133	55	-133	55
THRM-2816	THRM-T-NAVC-LA-ELEC	Navcam Electronics	OFF	35.0	-55	50	-128	50	-60	55	-133	55
THRM-2677	THRM-T-R-NAV-A-ELEC	Navcam Electronics	OFF	34.9	-55	50	-128	50	-60	55	-133	55
THRM-2550	THRM-T-L-NAV-B-CCD	NavCam CCD + Optics	OFF	34.9	-128	50	-128	50	-133	55	-133	55
THRM-2678	THRM-T-R-NAV-B-CCD	NavCam CCD + Optics	OFF	34.9	-128	50	-128	50	-133	55	-133	55
THRM-2679	THRM-T-L-NAV-B-ELEC	Navcam Electronics	OFF	35.0	-55	50	-128	50	-60	55	-133	55
THRM-2551	THRM-T-R-NAV-B-ELEC	Navcam Electronics	OFF	35.0	-55	50	-128	50	-60	55	-133	55
THRM-2592	THRM-T-MCL-FPA	MastCam Opto-Mech	OFF	34.9	-55	40	-128	50	-60	45	-133	55
THRM-2608	THRM-T-MCL-DEA	MastCam Electronics	OFF	34.9	-65	50	-128	50	-70	55	-133	55
THRM-2553	THRM-T-MCL-HTR A	MastCam Opto-Mech	OFF	35.1	-55	40	-128	50	-60	45	-133	55
THRM-2681	THRM-T-MCL-HTR B	MastCam Opto-Mech	OFF	35.0	-55	40	-128	50	-60	45	-133	55
THRM-2720	THRM-T-MCR-FPA	MastCam Opto-Mech	OFF	34.9	-55	40	-128	50	-60	45	-133	55
THRM-2736	THRM-T-MCR-DEA	MastCam Electronics	OFF	35.0	-65	50	-128	50	-70	55	-133	55
THRM-2554	THRM-T-MCR-HTR A	MastCam Opto-Mech	OFF	35.0	-55	40	-128	50	-60	45	-133	55
THRM-2682	THRM-T-MCR-HTR B	MastCam Opto-Mech	OFF	35.0	-55	40	-128	50	-60	45	-133	55
THRM-2588	THRM-T-MAHLI-FPA	MAHLI Opto-Mech	OFF	35.0	-55	40	-128	50	-60	45	-133	55
THRM-2627	THRM-T-MAHLI-HTR A	MAHLI Opto-Mech	OFF	35.1	-55	40	-128	50	-60	45	-133	55
THRM-2755	THRM-T-MAHLI-HTR B	MAHLI Opto-Mech	OFF	34.9	-55	40	-128	50	-60	45	-133	55
THRM-2609	THRM-T-CCMU-EBOX HTSINK	CCAM: tele,laser,RMI	OFF	35.1	-40	35	-40	50	-45	40	-45	55
THRM-2737	THRM-T-CCMU FPGA BRD	CCAM: tele,laser,RMI	OFF	35.0	-40	35	-40	50	-45	40	-45	55
THRM-2593	THRM-T-CCMU-OBOX-TELSCOPE	CCAM: tele,laser,RMI	OFF	35.1	-40	35	-40	50	-45	40	-45	55
THRM-2721	THRM-T-CCMU-OBOX-LASER IF	CCAM: tele,laser,RMI	OFF	34.9	-40	35	-40	50	-45	40	-45	55

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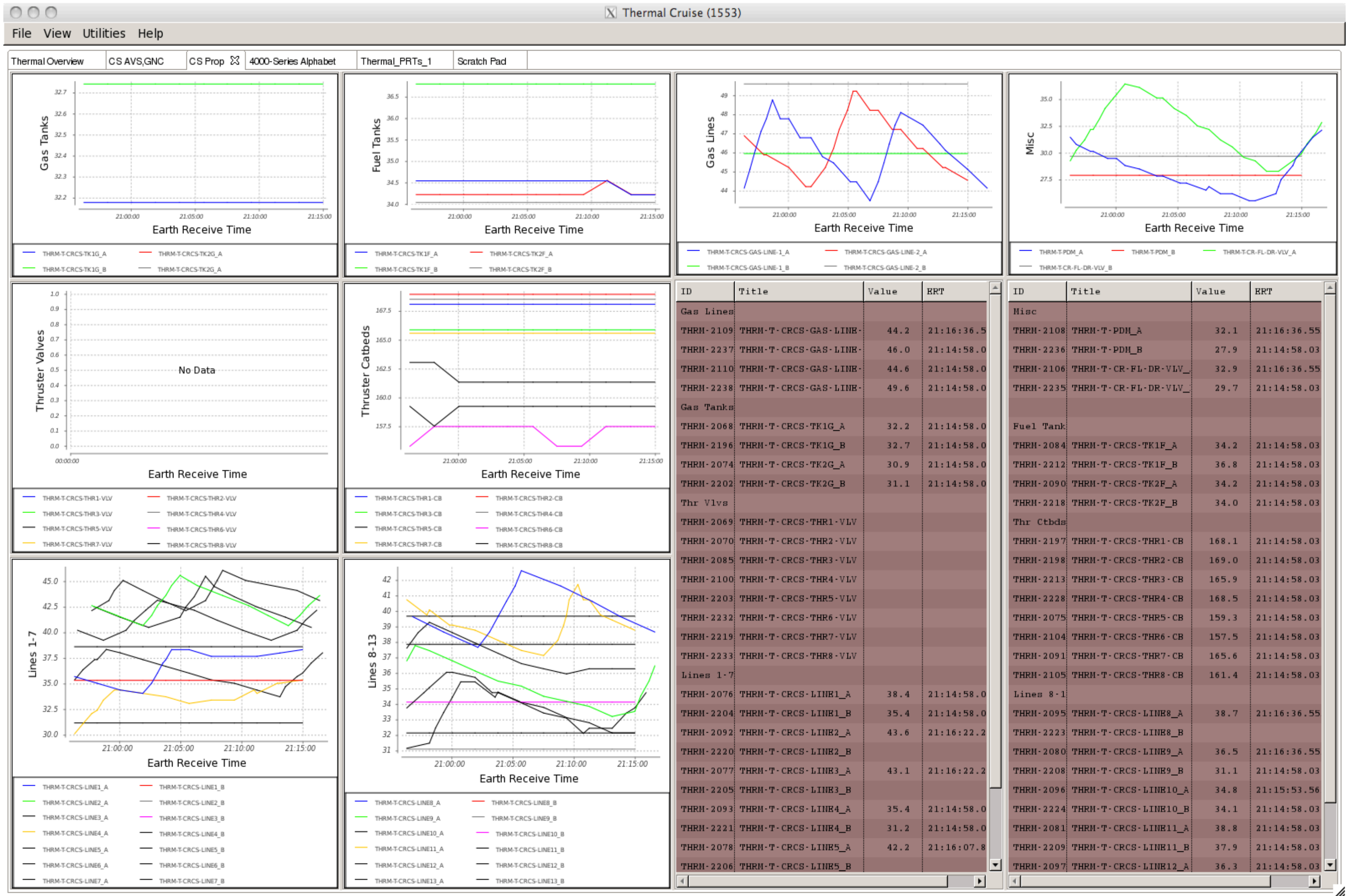
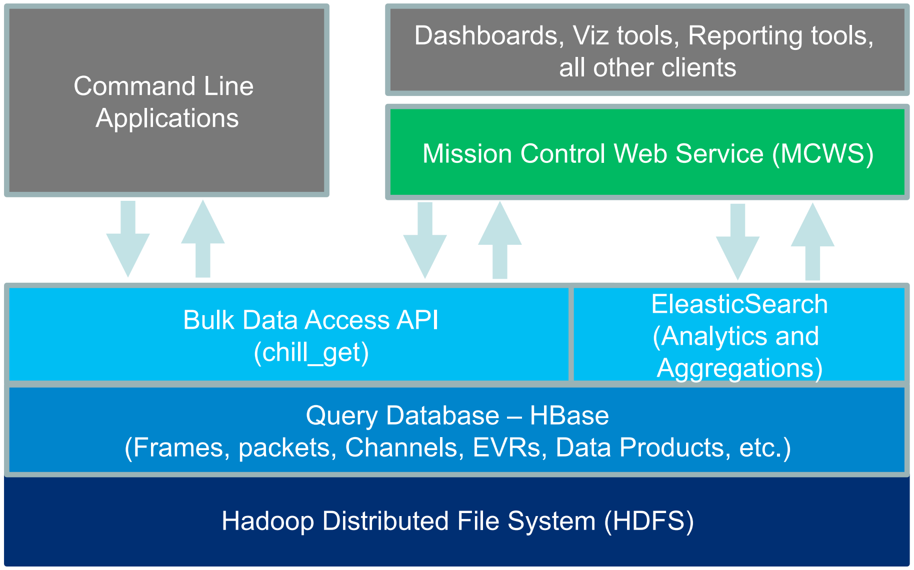
Example Display (custom grid)



FY16 and FY17 Plans

- Substantially improved realtime performance and throughput
- Support for CCSDS Space Link Extension (SLE)
  - Both Forward and Return Service interfaces
- Support for CCSDS CFDP File delivery
  - Both spacecraft-to-GDS and GDS-to-spacecraft
- Support for Operational commanding for non-smallsat missions
- High Speed Queries
  - Redesigning all data storage and query capabilities
  - Changing from MySQL to big data infrastructure
  - Will retain “chill_get” concept for backwards compatibility



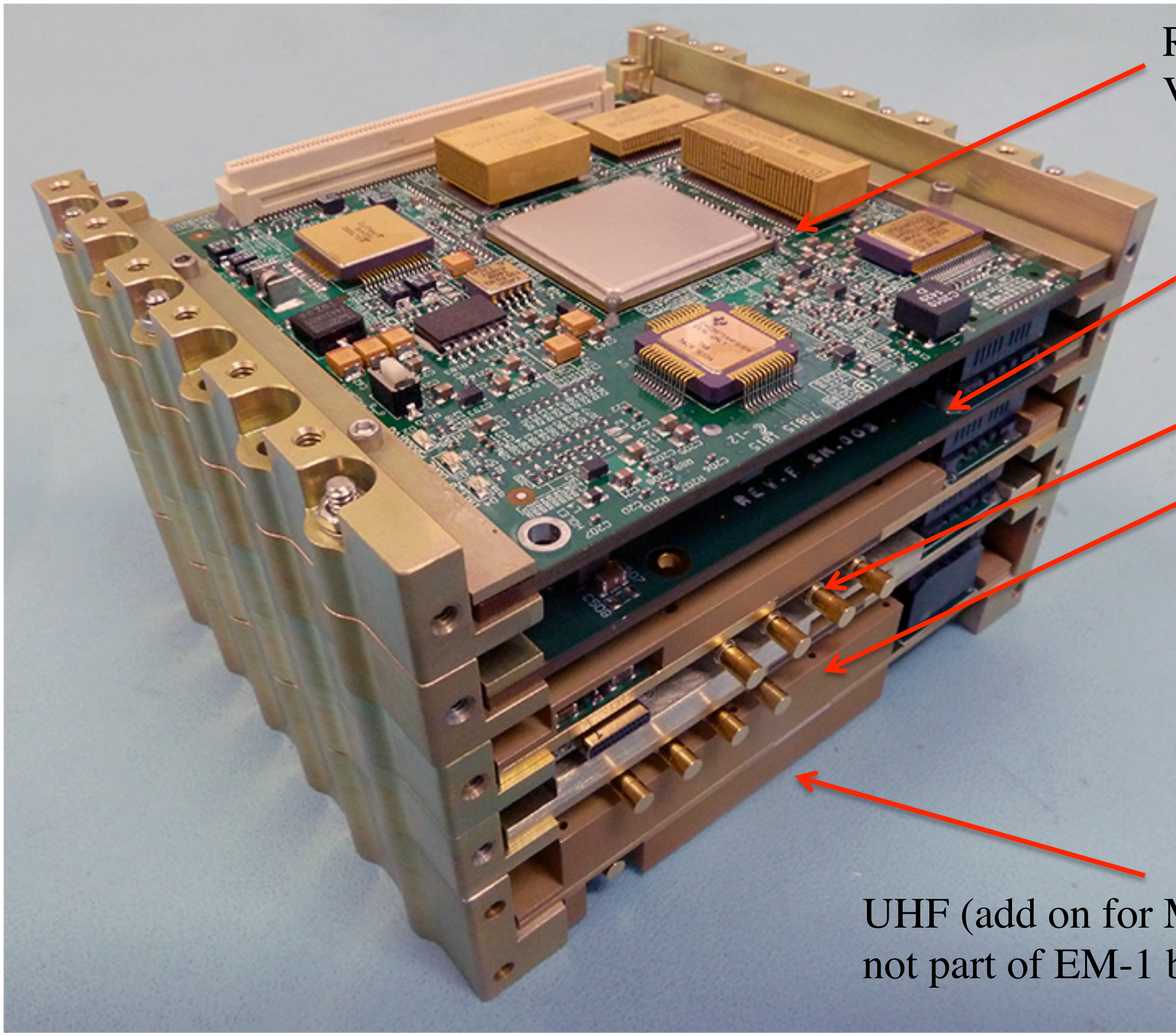
IND Cubesat Briefing/Technical Exchange
10 November 2015

Jet Propulsion Laboratory
California Institute of Technology

Iris Radio

Courtney Duncan & Kris Angkasa

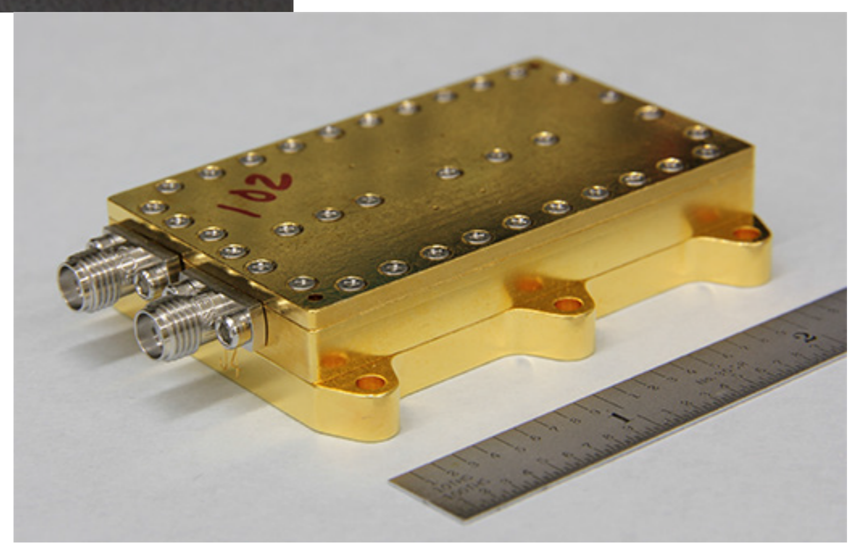
Iris V2 Stack

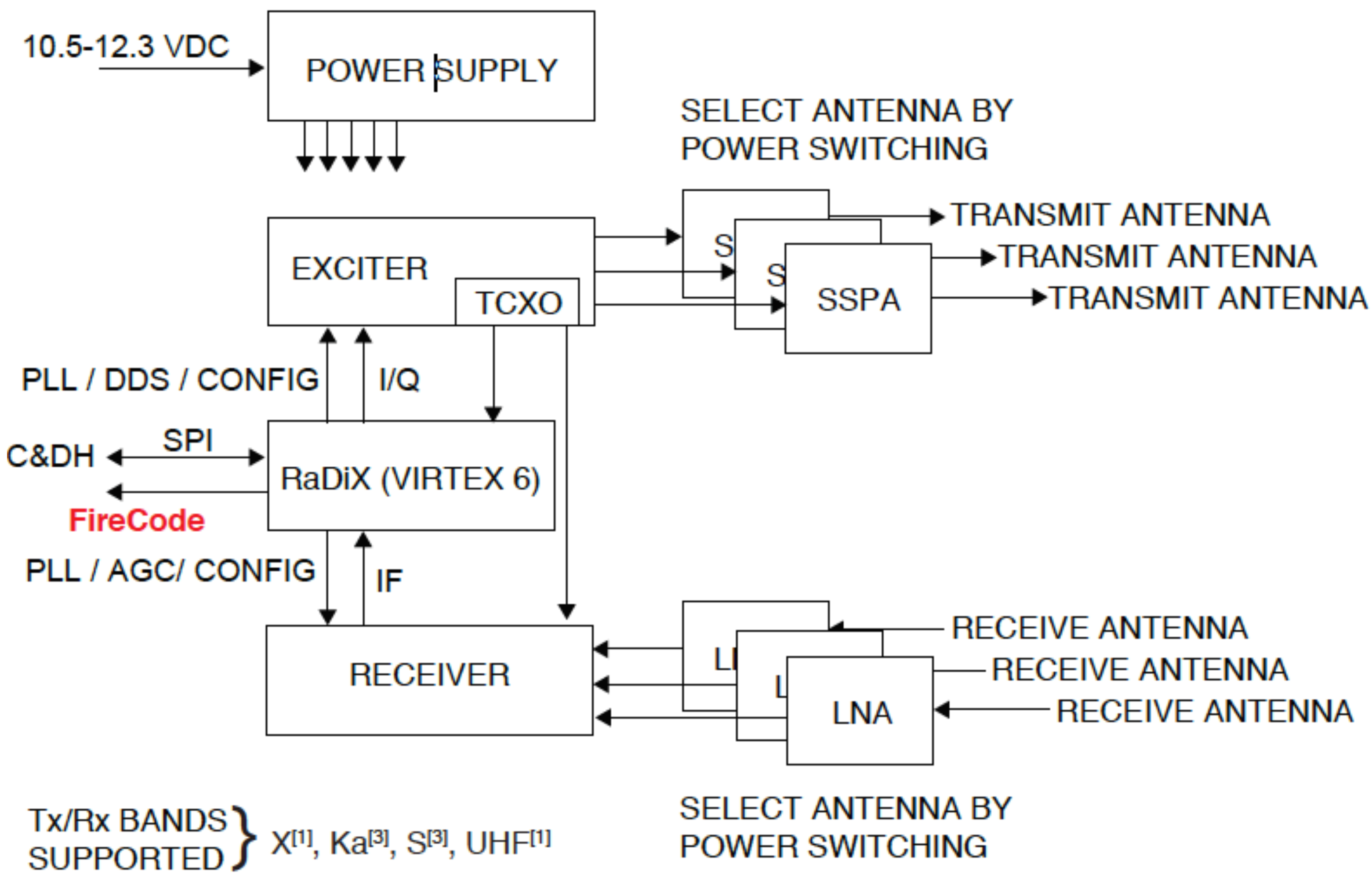


Iris V2 Additional Assemblies

2x LNA Assy.

3x 4W SSPA Assy.





Iris V2 Block Diagram

Iris is

- Board Stack – six assemblies
  - RaDiX digital board (Virtex 6 and memory)
    - 20 layer
  - Power Supply Board (PSB)
  - Exciter board (radio frequency transmitter)
    - Includes RF covers
  - Solid State Power Amp (SSPA) module
    - Mount on thermal radiator near antenna(s)
  - Receiver board
    - Includes RF covers
  - Low Noise Amplifier (LNA) module
    - Mount near antenna(s)
  - LGA (10x10cm board)
- All processing done in IP in Virtex 6
  - Firmware modems
  - Software on LEON3-FT softcore
  - JPL does/owns all the IP

Thermal and Power

- Iris V2 was redesigned from V1 for thermal reasons
  - Will operate indefinitely within these limits:
    - Operating AFT -20 to +50 C at chassis to radiator interface
    - (PF/Qual -35 to +62 C, Non-Op -40 to +85 C)
- Power Draw is the main limitation on CubeSat
  - @ 9 – 15 VDC
    - 0.1 W battery connect
    - 5.3 W C&DH interface only
    - 7.9 W receive only
    - 25.9 W full transpond

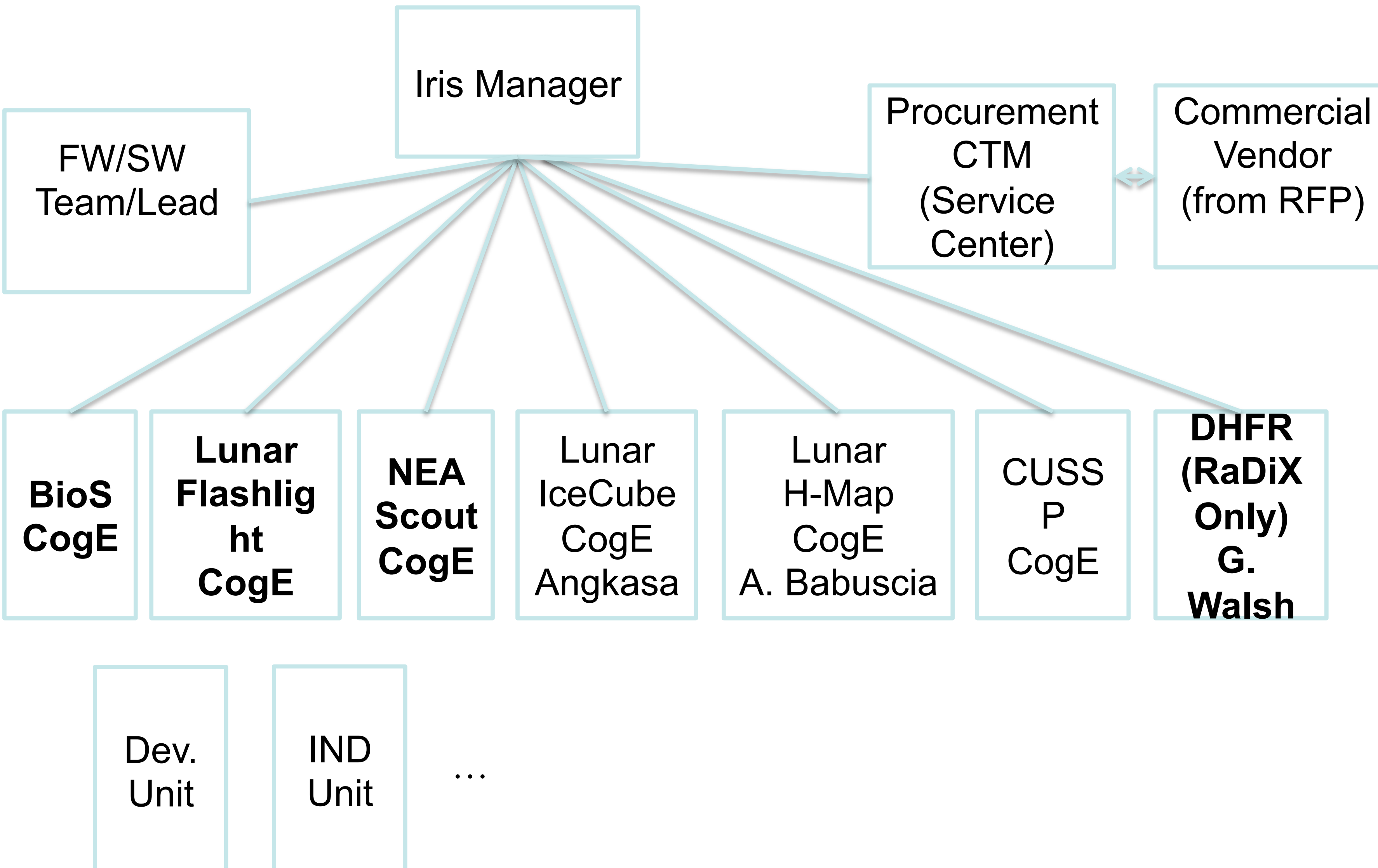
EM-1 Iris Transponder Group

- Need unified ERD consensus
  - Not project-by-project
- Group Buy specifications define
  - Mechanical ICD of three assemblies
  - C&DH interface
  - Supply voltage range
  - Current schedule has FM deliveries starting in Fall ’16
  - Requirements coordination through Cog team
- User Notes
  - Can start work from ML-605 development system
  - 1st customer conference was 9/22/15
  - Main restriction is that deltas from the group build are additional cost to project

JPL Support for Small AOs NextStep, SimpleX, Htides, possible others

- Cognizant engineer to perform the following:
  - Participate on Iris Cog team
  - Generate requisition procurement Iris V2 transponder and GSE from TBD contractor
  - Perform Contract Technical Management function for procurement of Iris transponder
  - Provide Iris ICD material to spacecraft designers
  - Generate any necessary handling and integration instructions document for telecom hardware
  - Review of reliability analysis and functional test data from vendors for procured items
    - (Functional testing to be performed at vendor)
  - Conduct DSN Test Facility (DTF) DSN Compatibility testing and certification
- Delivery is
  - One flight Iris subsystem
  - Cassy GSE
  - EIDP

JPL Iris Process – Cog Team



Iris is Not

- DSN tracking, telemetry and command (TT&C) setup
- JPL provided systems or navigation engineering
- Spares
- Flight cable harness
  - Except internal to Iris (i.e., stack to SSPA, LNA)
- Environmental testing (thermal vacuum, dynamics) or related fixtures (except S/C level testing)
- Reliability analysis if it does not exist from vendor

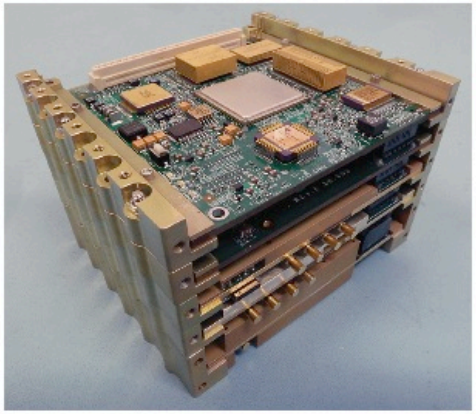
National Aeronautics and Space Administration

Iris V2 CubeSat Deep Space Transponder

X-, Ka-, S-Band, and UHF
Deep Space Telecommunications and Navigation

Features

- Deep Space Network Compatible
- Low Volume, Mass, and Cost
- Configurable Software Defined Coherent Transponder
- 0.5 U Volume
- 1.2 kg Mass
- 26 W DC Power Consumption at 5 W Radio Frequency Output, Full Transpond
- Deep Space Network Capability at X-Band Frequencies for Command, Telemetry, and Navigation
- Ka-Band, S-Band, UHF Options
- Passive (Conductive) Thermal Dissipation
- Radiation Tolerant Parts for Extended Deep Space Missions
- Configurable for Earth Orbit



Iris Version 2 is a CubeSat/SmallSat compatible transponder developed by the National Aeronautics and Space Administration's (NASA's) Jet Propulsion Laboratory (JPL) as a low volume and mass, lower power and cost, software/firmware defined telecommunications subsystem for deep space. Iris V2's features include 0.5 U volume, 1.1 kg mass, 26 W DC power consumption when fully transponding at 5 W radio frequency output (8 W DC input for receive only), and interoperability with NASA's Deep Space Network (DSN) at X-Band frequencies (7.2 GHz uplink, 8.4 GHz downlink) for command, telemetry, and navigation.

Iris V2 is designed with an environmentally robust architecture including radiation tolerant parts needed for deep space missions with durations of a few years and thermal management needed for navigation tracking sessions of several hours.

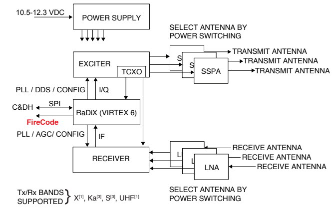
Iris uses a hardware slice architecture and reconfigurable software and firmware enabling extension and adaptation to new capabilities. Among those now planned are: Radio Science support (atmospheric and media measurements and occultations, gravity fields, radars, and radiometers); additional frequency bands (Ka-, S-, UHF); Disruption/Delay Tolerant Networking (DTN); proximity operations (at other planets such as Mars); Near Earth Network (NEN) compatibility; and Space Network (SN) compatibility.

Iris V2

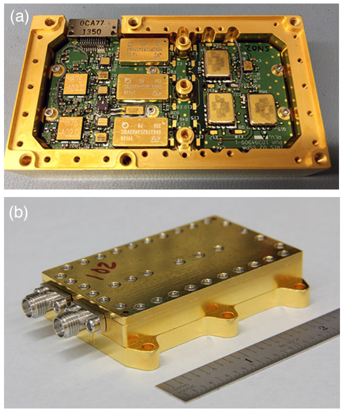
IND Cubesat Briefing/Technical Exchange

General Specifications	
Network Compatibility	DSN[1], NEN[3], SN[3]
Redundancy	Single string
Design Lifetime	3 years
Frequency Bands	X-band[1], UHF receive[1], Ka-[3], S-[2], UHF transmit[3]
Envelope	104 x 118.5 x 65 mm
LNA Envelope	75.5 x 43 x 13 mm
SSPA Envelope	87.5 x 43 x 23 mm
Flight Operating Temperature	–20 to +50°C
Solid State Power Amplifier	3 RF paths, dedicated to 3 antennas, path selectable via power switching
Low Noise Receive Amplifier	3 RF paths, dedicated to 3 antennas, path selectable via power switching
VCO	Internal TCXO[1], external 10 MHz[3]
TCXO Allan Deviation	10^{-9} at 1 sec (non-coherent operation)
Ranging Delay Variation	< ±30 nsec
Telemetry Symbol Rates (downlink)	62.5 bps[1] 8 k[1] 1.024 M[3] 125[2] 16 k[1] 2.048 M[3] 250[1] 32 k[2] 4.046 M[3] 500[2] 64 k[1] 8.192 M[3] 1 k[1] 128 k[2] semaphores — (< 62.5 bps)[3] 2 k[2] 256 k[1] Other arbitrary rates[4] 4 k[1] 512 k[3]
Subcarriers, Downlink	25 kHz[1] 281.25 kHz[1] Arbitrary subcarriers to 10 MHz[4] Direct carrier modulation[2]
FPGA	Virtex 6 (–130[2], –240[3])
CPU	Gaisler LEON3-FT softcore (on Virtex 6)
Memory	32 Mbit non-volatile NOR-Flash (radiation tolerant) 16 Mbit volatile SRAM (radiation tolerant) 4 Mbit volatile EDAC SRAM (radiation tolerant)
Interface	Point-to-point SPI
Launch Capability	Non-operational at launch
Radiation, SEE Levels (100 mil (Al))	LET >37 MeV–cm²/mg (Virtex 6), 20 krad (ELDRS to 5 krad)
Telemetry Encoder	Firmware encoder
Command Detector	Firmware decode with FireCode (spacecraft reset direct command)
Mounting	CubeSat stack in chassis with separate SSPA and LNA modules
Carrier Loop BW	Configurable (20 Hz typical)
Command uplink rates (bps)	62.5[1] PM/PSK/NRZ 2000[2] 125[2] 4000[2] 250[2] 8000[1] 500[2] Arbitrary rates[4] 1000[1]
Command uplink subcarriers	16 kHz[1] Arbitrary subcarriers[4] Direct Carrier modulation[2]
Command/Telemetry Interface	Command and Telemetry Dictionary[1], configurable[4]

[1]Compatibility verified in Version 1 and/or Version 2.
[2]Compatibility supported in Version 2 but not yet verified.
[3]Capability under development or planned.
[4]Capability supportable due to software/firmware reconfigurability.



Iris V2 Block Diagram



Iris V2 SSPA (a) and LNA (b) are mounted separately for thermal reasons.

Iris V2

Mass and Power	
Stack Mass	1000 g including thermal enclosure (no UHF) not including cables
SSPA Mass	130 g
LNA Mass	70 g
Input Supply Voltage	10.5–12.3 VDC[1], 9–15 VDC[2]
Input Supply Power	0.5–26 W (see power states)[1]

Iris Mode	DC Input (W)
Battery Connect	0.5
FPGA On (Start-up)	5.3
X-Receive Only	7.9*
X-Transmit Only	23.3
X-Transmit/Receive	25.9

*5.5 W receive-only mode[3].

Transponder Specifications	
X-Band Uplink Frequency Range	7.145 – 7.190 GHz (channel assignment programmed in firmware)[1] 7.190 – 7.235 (near Earth supported)[2]
X-Band Downlink Frequency Range	8.400 – 8.450 GHz (channel assignment programmed in firmware))[1] 8.450 – 8.500 (near Earth supported)[2]
Other Bands	S-Band: Deep Space[3]/near Earth[3] Ka-Band: 32/34 GHz Deep Space[3]; 26 GHz near Earth[3]
Coherant Turnaround Ratio	880/749[1], standard S- and Ka-Band ratios[3], arbitrary ratios[4]
UHF Frequency Range	390–450 MHz receive[2], transmit[3]

Receiver Specifications	
Noise Figure	5 dB X-Band and UHF[1]
Carrier Tracking Signal Range	–70 to –130 dBm[1]
Tracking Range	100 MHz[1]
Ranging Filter Type	Digital
Ranging Filter	2000 kHz

Exciter (X-Band)	
8.4 GHz Output Power (SSPA)	37 dBm (5 W) (–15 dBm drive from exciter)
X-Band Phase Noise (1 Hz offset) (100 Hz – 100 kHz offset)	TBM (–80 dBc) TBM (–135 dBc)
X-Band Spurious & Harmonic Outputs	< –40 dBc (–60 dBc at SSPA)
TLM Encoding	Convolutional 15-1/2[2] Convolutional 15-1/4[2] Convolutional 7-1/2[1] Manchester, Bi-Phase, and bypass (NRZ)[1] Reed Solomon (255,223)[1] Turbo 1/2[2] Turbo 1/3[2] Turbo 1/6, block size 8920 bits[1]
TLM Phase Deviation	0 to 180 degrees[2]
Diff 1-way Ranging (coh w/DL carrier)	X-Band 2F1: 19.2 MHz[1] programmable modulation index 17.5° typical

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[2]Compatibility supported in Version 2 but not yet verified.
[3]Capability under development or planned.
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Iris V2

IND Cubesat Briefing/Technical Exchange

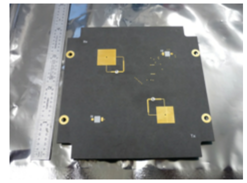
Suggested CubeSat Antennas & Data Rates to DSN 34 m

for 70 m, multiply rates by 4

for 20 m, 100°K, divide rates by 10

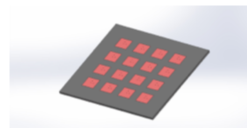
- LGA — Single Tx & Rx patches on 10x10 cm face
- Included with Iris V2
- 5 dBi gain — wide field-of-view
- 1 Mbps at Moon

Mars ~1 AU (bps)		
Opposition	Arrive	Conjunction
31	10	1



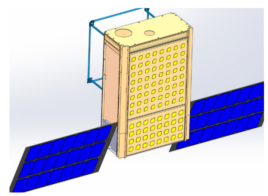
- MGA — 4x4 Tx patch array
- Fits 10x10 cm face
- 16 dBi gain (needs pointing)

Mars ~1 AU (bps)		
Opposition	Arrive	Conjunction
500	125	16



- HGA — 8x8 Tx patch array
- 20x20 cm flat panel (6 U)
- Deployable w/solar panel (NEA Scout)
- 21 dBi gain (needs good pointing)

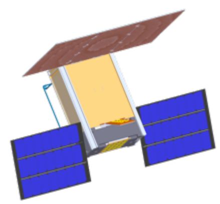
Mars ~1 AU (bps)		
Opposition	Arrive	Conjunction
1000	250	62



- VHGA — Tx reflect array
- Deployed on 6 U (MarCO) 3 panel
- 28 dBi gain (needs good pointing)

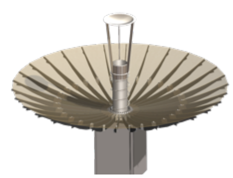
Mars ~1 AU (bps)		
Opposition	Arrive	Conjunction
4000	2000	250

- Ka-Band 3 U Turkey Tail version also in development



- KaPDR — Ka Parabolic Reflector (0.5 m) in development
- Deployable from 10x10 cm face (3 U)
- >40 dBi gain (needs very good pointing)
- 32/34 GHz @ 2 W RF

Mars ~1 AU (bps)		
Opposition	Arrive	Conjunction
512k	128k	32k



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